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Crown fire spread rate modeling

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"Crown Fire Spread Rate Modeling"
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Objectives and synopsis of progress

The research reported here is a part of a continuing collaborative effort between the Fire Behavior Research Work Unit of USDA Forest Service, Fire Sciences Laboratory, Missoula, Montana, the Canadian Forest Service, the provincial government of the Northwest Territories (NWT) of Canada, and the Mechanical and Industrial Engineering Department of MSU Bozeman, known as the International Crown Fire Modeling Experiment. This program has included field experiments involving crown fires in mature Jack Pine burned near Fort Providence, Northwest Territories, Canada, and computer simulation model development in Bozeman and Missoula. The objective of the research reported here was to test and evaluate a radiation-driven crown fire spread rate model against data taken in the NWT burns during the summers of 1997 and 1998.

If the model is deemed to be sufficiently accurate in predicting the spread rates of the test fires, it may be used in future as part of a landscape scale simulation of wildland fire spread designed for use in predicting local and remote air quality impacts of prescribed and unintentional wildland fires.

Substantial progress has been made in identifying and correcting weaknesses in the suite of computer algorithms comprising the radiation driven crown fire spread rate model (RDCF3) developed under previous joint US and Canadian sponsorship. The model has been revised and exercised using fuel and environmental data from five burn plots in NWT. The raw input data, their manipulation to create representations for use in the spread rate model, and output from the spread rate simulation model were documented in a progress report [Albini 1999] delivered in August. The RDCF3 version of the model, using data processed by the input preparation module being used in March 1999, failed to perform adequately and would not predict spread rates at all for some fires.

The model was revised to make fuel particle cooling by natural convection sensitive to particle diameter, to compute flame geometry using a modification of the algorithm in the original model, and to use in the flame geometry computations the wind speed relative to the moving fire front, as documented here. The revised model is identified by its main program name, RDCFX2.

The data preparation portion of the computer code suite was also modified to provide the equivalent, single size class fuel particle properties derived from weighted averages based upon relative mass of fuel consumed as a function of particle size class, to impose a weighting factor that is a function of particle diameter, to account for delayed burning of fuels with diameters greater than a few cm, and to maintain the optical opacity properties of each fuel layer. This modified input preparation algorithm is made thermodynamically rigorous by weighting intrinsic fuel properties by the quantity of fuel consumed. It is posited that the burning of larger particles would not influence flame geometry because the fuels would be consumed after the passage of the main fire front. And maintenance of the optical opacity properties of the fuel layers is fundamental to the veracity of a simulation of fire spread based upon radiation heat transfer. These data preparation revisions are embodied in a new version of subroutine SINGLE included in the data preparation program INPREPZ2. These revisions substantially improved the performance of the model, but there are still substantial differences between observed crown fire spread rates and the spread rates predicted by the revised model.

While these results are encouraging, they do not validate the crown fire spread rate model. The radiation intensity properties used to describe the test fires are not inconsistent with the radiation measurements, but they are not the only values one might choose from the data. Because predicted spread rates are quite sensitive to these radiation intensity descriptors, and because these values have proved to be very difficult to measure, predictions of crown fire spread rates *ab initio* will have substantial uncertainty ranges. Use of the model for hypothetical fire growth simulations to compare alternative courses of action may not require a high degree of absolute accuracy, however.

Radiation data

A cursory review of some of the radiometric data [Butler 1999] from plots A, 5, and 6, burned in 1997 revealed that there was a large amount of variation with time in the sensed radiation intensity from the free flame and from the burning zone. There were "drift" variations with time scales on the order of tens of seconds, and high frequency variations with one second or sub-second time scales. The low frequency variations of the sensed free flame radiation intensity are probably due to absorption of radiation by the air and variation of flame radiation intensity with position in the flame. The high frequency variations are probably due to intermittency of the flame radiation output and/or intermittent obstruction of the radiation by smoke. The low frequency variations in the sensed intensity of the radiation from the burning zone are masked or dominated by extinction of the radiation by the vegetation in the path between the source and the sensors. The causes for the high frequency variations of these signals, although considerably less pronounced than those of the free flame signals, are more difficult to explain.

Peak radiation intensities inferred from short-term average signals from the burning zone of plot A can be interpreted as radiometric temperatures as high as 1500 K. Longer term averages by visually smoothing the signals give temperatures more like 1250 K, which seems more heuristically appealing. The same signals from plot 5 gave a burning zone radiometric temperature of 1100 - 1200 K. The ratio of the free flame radiation intensity to that of the burning zone was about 0.3 to 0.35 for plot 5, and was not available in the data from plot A.

It was determined that the preliminary trials of the crown fire spread rate model would be conducted using burning zone radiometric temperatures in the range of 1200 - 1300 K and a ratio of flame intensity to burning zone intensity equal to 0.30 - 0.35. The use of less than peak temperatures is indicated because the model does not take account variation of intensity with distance due to atmospheric absorption or variation of flame radiation with height. The expected intermittency, obstruction, and atmospheric attenuation are to be reflected in the use of reduced figures for the effective radiometric temperature and the flame/burning zone intensity ratio parameter.

Fuel Descriptions

In order to use the radiation-driven crown fire prediction model, the fuels in as many as three layers must be described. The layers are nominally the live crown layer, a subcanopy (or stem space) layer, and a surface layer. Each of the layers is described as being uniformly and homogeneously populated by a collection of randomly distributed and randomly oriented cylindrical fuel particles, each category of which is characterized by its diameter (as surface area to volume ratio), mass density, ash content, heat of combustion, and moisture content. Most conifer forest fuels readily fit into these categories, and Canadian forestry practice is to categorize components as foliage or as roundwood of diameter < 0.5, 0.5-1, 1 - 3, 3 - 5, 5 - 7, and > 7 cm. Tree boles are accounted separately and their vertical orientation obviously violates the model assumption of randomness (the effect is to make them appear to have a diameter larger by a factor of $4/\pi$ than actual, and this is not compensated).

Each of the experimental burn plots and smaller test plots was subject to extensive mensuration by Canadian Forest Service personnel during and following the period of site preparation. Overstory and understory stockings were established and reported in terms of numbers of live and dead trees per hectare and the mean and standard deviation of diameter at breast height outside bark (dbh) for trees with dbh of at least 3 cm and of height greater than 1.3 m. Live and dead trees of lesser stature and/or lesser dbh were reported separately in terms of mean and standard deviation of tree height, mean number of stems per hectare, crown base height, and dry weight loadings (kg/m^2) of foliage and live and dead roundwood of diameter less than 0.5 cm. Dead and down woody fuels were inventoried by diameter class, and loadings of sound and rotten reported. These were the principal surface fuels, as minor vegetation (kinnikinnick, pixie-cup, feathermoss, etc.) was so sparse as to contribute negligibly to total fuel loading. Duff (litter and fermentation layers) depth was determined and loading burned established by depth reduction measurements, but for the purpose of modeling the crown fires, only a small and arbitrary amount of dead needle

litter (half the loading of the dead roundwood under 0.5 cm) was included to represent jack pine needle drape, and the more compact duff was not included.

Allometric equations [Alexander, 1999] were developed from destructive sampling data, allowing estimation of the quantity and vertical distribution of fuel components by size class and category (live or dead) given the species, category, and dbh of the specimen tree. In order to estimate the vertical distribution of the total quantity of fuel in each size class, it was assumed that the distribution of tree diameters was uniform over an appropriate dbh range. The minimum and maximum diameters were adjusted for the distributions in each plot, tree species, and category, to yield the measured mean and standard deviation of dbh. In a few pathological cases, for understory black spruce, the standard deviation was too great to fit a flat distribution. This observation indicates that the true distribution was bimodal, implying two distinct black spruce germination events, some number of years apart. In these cases the sample standard deviation was artificially reduced to permit a flat distribution within the allowable dbh range to be used.

The flat distributions were then sampled in 1-cm increments and allometric equations used to determine tree height, height of crown base, and loadings by size class and category. For overstory jack pine, foliage and live and dead limbwood were uniformly distributed throughout the live crown height range for living trees, for example. A contribution for tree boles was calculated, assuming linear taper of diameter from dbh at 1.3 m (nominal breast height) to zero at predicted tree height. A similar procedure was used to distribute the loadings from understory trees. The smallest trees had crown bases that were essentially at the surface, so their predicted loadings were simply distributed uniformly over their mean heights. Examples of the results of this procedure are shown in figures 1 - 5.

Figure 1 shows the inferred vertical distribution of live jack pine needles for test plot A. For each tree diameter class considered, the total loading of its foliage was assumed to be distributed uniformly between its predicted live crown base height and its tree height. The number of trees in each diameter class was calculated from the dbh range and the total number of trees per hectare. In this manner the total foliage loading was accumulated at each height, in 25 cm thick height slices and plotted in figure 1. Note that there are no jack pine needles below 4 m height and none above 16 m. The cumulative loading below a given height is plotted in figure 2; this is quite a smooth curve. Such data were used to establish the height of the base and the top of the live crown layer for each plot. The crown layer base height was taken to be the height below which 10% of the jack pine foliage existed and the top of the layer the height above which 10% existed.

Figure 3 shows the inferred distribution of black spruce foliage for plot A. Note the abrupt rise to a peak at 2 m and the gradual falloff to zero at 8 m. There is predicted to be a height range of about 4 m in which both types of foliage exist. But note, from figure 4, that the cumulative distribution of black spruce foliage shows that only about 5% of the foliage exists above the lower bound of the crown layer at 6.8 m. This conveniently fits with the assumption of the model that the layers are distinct.

Figure 5 shows the vertical distribution of jack pine foliage for plot 5. Also shown on this graph are the predicted heights of the live crown base and top. The base is at 5.55 m and the top at 11.6 m. Both these values agree with the visual impressions of most on-site viewers. The nearly uniform foliage loadings shown in figures 1 and 5 are also supportive of the model assumption that the layers are uniform and homogeneous. Complete fuel layer data for each of the five plots (A, 5, 6, 7, and 8) that were burned in 1997 and 1998 are given in tables 1 - 5.

These complete fuel descriptions were input to the data preparation program INPREP [Albini 1997] and later INPREPZ2, which reduced the composite fuel descriptions of each layer into a single size class equivalent fuel loading [Albini 1996, Call and Albini, 1997]. The equivalent single-component fuel communities, along with environmental data (see tables 6 - 10), were then processed by the crown fire spread rate model.

Preliminary results and model revisions

Using the data processed by INPREP, the radiation-driven crown fire spread model was exercised to predict fire spread rates for the five burned plots. The original model (RDCF3) described in Albini [1997] was modified to allow a finer longitudinal discretization. The limitation of the earlier version was imposed by the capability of the 16-bit FORTRAN compiler in use then. Using a new 32-bit compiler permitted the use of as many as 1000 longitudinal and 50 vertical slices. This version of the program was otherwise identical to the model RDCF3.

The predictions of this model were entirely unsatisfactory. The basic approach of the model is to use an assumed value for the rate of fire spread to calculate a flame height and tilt angle, then use this flame geometry to predict the rate of spread of the fire. By doing this twice, and assuming a linear relationship between the assumed rate of spread and the predicted rate of spread arising from that assumed, the "equilibrium" spread rate can be determined and verified by another model exercise [Call 1997]. The results showed that the model did not perform at all satisfactorily. In some cases, the attempt to compute a predicted spread rate was simply abandoned because of repeated failures of the iteration scheme.

Possible sources of the fundamental defect in the RDCF3 model revealed by these trials were sought. The most likely suspects identified were (not in any particular order and surely an incomplete list):

- 1) Lack of a "clear air" extinction parameter for radiation.
- 2) Improper accounting for convective cooling of solid fuel particles.
- 3) Failure of the hypothesis that there exists an equivalent single-component fuel layer that can represent each of the complex multi-component fuel layers that actually exist.
- 4) Inappropriate fuel-consolidation manipulations, resulting in inadequate discounting of large fuel size classes resulting in an oversized "equivalent" single size class.
- 5) An inadequate model for flame geometry.

The first listed deficiency could be corrected, but would require a substantial effort in coding and debugging. It was not thought to be possible to make such a revision in the time frame of the current study effort. Restructuring the model to accommodate the third possibility would take even longer, and would result in a model that probably could not be run on a personal computer. It would require a vector processor to track the temperature histories of a large number of fuel particle categories with different size classes and moisture contents.

The second defect was readily repairable and the fourth and fifth possibilities amenable to investigation during this study. In the early stages of model development, only the foliage of the crown layer was actually modeled. To simplify computation, a fixed lower limit value of 0.35 was used for the Nusselt number, a dimensionless quantity proportional to the film heat transfer coefficient used to model natural convective cooling of the solid fuel particles. When the model was revised to consolidate all the different fuel particles of each fuel bed layer into a single equivalent particle category, the Nusselt number should have been reformulated to be a function of particle diameter. A robust correlation between the Nusselt number, Nu , for natural convection heat transfer, the Grashoff number, Gr , and the Prandtl number, Pr , has been available for many years. The relationship is that shown in figure 25-3 of the classic textbook by Jakob [1956]:

$$Nu = 0.55 (Gr \cdot Pr)^{1/4}$$

where

$$Nu = h D / k$$

$$Gr = g D^3 \theta_s / \nu^2 T_o \text{ (assuming air be an ideal gas)}$$

$$Pr = \nu / \alpha = \nu \rho C_p / k = 0.72 \text{ for air}$$

and

- h = film heat transfer coefficient, $W / m^2 K$
 D = particle diameter, m
 k = thermal conductivity of air, $W / m K$
 g = acceleration of gravity, m / s^2
 θ_s = temperature difference between particle surface and ambient, K
 ν = kinematic viscosity of air, m^2 / s
 α = thermal diffusivity of air, m^2 / s
 T_o = ambient temperature, K
 ρ = density of air, kg / m^3
 C_p = specific heat capacity of air at constant pressure, $J / kg K$.

The air properties are nominally to be evaluated at some mean temperature of the thermal film, between the particle surface temperature and ambient. Here it was assumed that the ambient temperature is 300 K and the particle surface temperature 335 K, about halfway between ambient and the boiling temperature of water, where convective cooling is most important. These assumptions lead to the simplified form:

$$Nu = 126 \sigma_c^{-0.75}$$

where σ_c is the surface area / volume ratio of the single size class equivalent fuel particle of the layer in question. This revision was coded with a lower limit of 0.35 for Nu. The single size class fuel particles invariably are of larger diameter than the foliage components – and sometimes considerably larger – so each fuel layer experiences cooling by natural convection at a rate more appropriate to its larger particle size. The model incorporating this single revision was named RDCFX.

Unfortunately, making only this single revision did not improve model performance significantly. Five personal computers were dedicated to the task of running the model with burning zone radiation temperature set to 1050K and the flame radiation reduction factor to 0.40. After more than three days (80 hours) of continuous computation, the results revealed that the model required further revision. Even with reduced input radiation zone temperature, the model was failing to predict reasonable spread rates. It seemed that the single size class fuel beds were composed of too unrealistically large particles and the fire intensities for the assumed rates of spread were too great, giving rise to unrealistically large flame structures. The fourth and fifth items listed above were next addressed.

The fourth listed possible defect was remedied by a revision of subroutine SINGLE used by program INPREP to consolidate the complete fuel component list for each layer into a single size class equivalent. The original version of INPREP calculated the expected diameter reduction of each particle size class and used this factor to discount the loading of that size class, keeping most other physical properties of the fuel bed constant. In addition to this reduction factor, it was proposed that an additional discounting factor be introduced. The extra discounting factor, e , is to be imposed on larger size classes through use of a reduction factor of the form:

$$e = \begin{cases} 0, & \sigma \leq 200 \text{ m}^{-1} \\ t^2 (3 - 2t), & 1200 \text{ m}^{-1} > \sigma > 200 \text{ m}^{-1} \\ 1, & \sigma \geq 1200 \text{ m}^{-1} \end{cases}$$

where

$$t = \frac{\sigma - 200}{1000}$$

This arbitrary discounting factor changes smoothly from unity for particles less than 3.33 mm in diameter to zero for particles greater than 2 cm in diameter. Its purpose is to consign the consumption of larger size particles to the region of continued burning behind the leading edge of the crown fire, rather than to combine them with the foliage and fine fuels that contribute to the edge intensity of an advancing crown fire. Incorporation of this discounting factor to reduce the loading of larger diameter fuels increased the relative contribution of the crown layer to the fire intensity while decreasing that of the surface fuels. With this revision, the single-component equivalent fuel layers for the five burn plots being investigated became much closer to the fine fuel loading and less distorted in terms of particle size and mass density.

This arbitrary revision was still heuristically incomplete because it simply ignored the existence of fuel components larger than 2 cm diameter and thereby reduced the optical opacity parameter for fuel layers that contain such components. But it did move the model in the proper direction of reducing the fire intensity and flame height for any given spread rate assumed. The nature of the equivalent single size class fuel bed produced by the original INPREP algorithm is one with unreasonably large diameter fuel particles of completely unrealistic mass density.

Recall that the original algorithm relied upon maintenance of most of the physical characteristics of the fuel bed, including the void volume fraction and the optical opacity parameter, or total fuel surface area per unit volume [Albini 1996]. It is these two constraints that lead to the unrealistically large and low density fuel particles of the equivalent bed. If maintenance of the void volume fraction at a constant value is relaxed, the algorithm can be revised to a much more appealing one in which the equivalent fuel particle intrinsic properties, and the fuel moisture, are established by computing a weighted average based upon the fraction of total mass consumption that is contributed by each particle class. The new algorithm uses the same fuel particle fractional diameter reduction formula as before:

$$\delta_i = \min(1, a \sigma_i / \rho_i (1 + bM_i))$$

where the empirical constants a and b were estimated to be [Call and Albini, 1997]

$$\begin{aligned} a &= 1.66 \text{ kg / m}^2 \\ b &= 4.95 \end{aligned}$$

The fraction of mass loading consumed for particle size class i is given by

$$g_i = 1 - (1 - \delta_i)^2$$

and the total mass loading consumed (hence the single particle equivalent mass loading, W_e) by:

$$W_e = \sum_i g_i W_i$$

In the original formulation of INPREP, the fraction g_i was used as a weighting factor to establish a weighted average for each of the intrinsic ("per unit mass") properties of the equivalent fuel loading, including moisture content. But a more appropriate weighted average is one based upon the fraction of total mass consumption contributed by each particle class. The weighting factor for equivalent particle density, specific heat capacity, ash fraction, and moisture content should be f_i , where

$$f_i = g_i W_i / W_e$$

Using this weighting factor maintains the proper thermodynamic relationships. Keeping the optical opacity parameter constant allows computation of an equivalent single particle surface area to volume ratio as:

$$\sigma_e = \frac{\rho_e}{W_e} \sum_i \frac{\sigma_i W_i}{\rho_i}$$

Finally, to retain the fire edge intensity-reduction obtained by introducing the extra discounting factor e described above, the heat of combustion of the equivalent fuel particles can be reduced by using the factor e , based upon the individual particle size classes, so the equation for the equivalent particle heat of combustion, H_e , becomes:

$$H_e = (1 - \alpha_e)^{-1} \sum e_i f_i (1 - \alpha_i) H_i$$

where e_i is computed from the formula for e above, using σ_i , the surface area to volume ratio of the particle size class i .

This revised method of computing a single size class equivalent fuel bed is incorporated into subroutine SINGLE in the version of the INPREP program identified as INPREPZ2. The effect of this revision on the performance of the model was significant, but exercises of the model at higher wind speeds than those experienced during the experimental burns showed that the model frequently predicted *decreases* in fire spread rate with increasing wind speed. The problem was diagnosed as due to the singular behavior of the flame structure model at low wind speeds. Therefore the flame structure model was revisited.

In the original presentation of the model [Albini 1981] it was noted that the proposed simplified form predicted a flame length that was infinite at zero wind speed. The predicted flame length for low wind speed decreases as (wind speed)⁻¹, reaches a minimum value and then rises slowly with increasing wind speed. The minimum flame length was found to be proportional to the fire intensity to the power 2/3, which is the proper exponent from similarity considerations. It was further noted that the flame length would be doubled from its minimum value only by decreasing the wind speed to 1/5 its value at the minimum, or by increasing it to 5 times its value at the minimum flame length.

Since the wind speed is never long constant, and the response time for crown fire flame structure to respond to wind speed changes is on the order of seconds, it is unlikely that the flame geometry observed in the field ever actually represents what would be present if the wind speed profile were simply the long term average value. Based on these considerations, it seems that a useful flame geometry model could be based upon a flame length that would be a modest multiple of the predicted minimum value, dependent only upon the fire intensity. The flame tilt angle formula relating wind speed, tilt angle, and flame height could then be solved by replacing the flame height by the product of the flame length and the cosine of the tilt angle. This is what was done to create the new flame geometry model (subroutine xflame) that is incorporated into the revised spread rate prediction model. The flame length in meters, L_f , is predicted from the fire intensity, I , in kW/m, using

$$L_f = 0.0175 l^2$$

This flame length is 25% greater than the minimum value predicted by the model, being the average flame length over a range of wind speed from 3.5 to 1/3.5 times that at the minimum flame length. Using this flame length prediction, the geometrical relationship and the tilt angle equation provide flame height and tilt angle:

$$\tan(\alpha) = \frac{\sqrt{1 - (H/L_f)^2}}{H/L_f} = \frac{H}{\int_0^H u(z) dz / \left(\frac{2}{3} gH\right)^{1/2}}$$

where α is tilt angle, H is the flame height, g the acceleration of gravity, and $u(z)$ the average wind speed z at meters above the canopy top. For this latter relationship, a logarithmic variation of mean wind speed with height is used [Albini and Baughman 1979].

Finally, because the spread rates of some of the NWT fires proved to be a substantial fraction of the inferred crown top wind speeds, the code was revised to employ the flame structure model using the *relative* wind speed at crown top to scale the wind profile. This improper scaling was used because it was simple to implement and keeps the wind direction constant with height. The algorithm may be further revised in the future. The model incorporating all the above revisions is named RDCFX2. Exercises of the revised model did not predict the actual rates of spread of the tests fires with precision (see table 11) using constant values for the radiation intensity parameters, but provided realistic ignition interface shapes (see figure 6) and heuristically appealing variation of spread rate with wind speed (see figures 7 - 11).

Conclusions and extensions to landscape scale fire growth simulation

The revised model performs in a manner that is heuristically satisfactory, but the sequence of iterations is very slow to converge. On the average it took about four days (100 hours) on a continuously running PC (133 MHz Pentium) to predict a rate of spread for an assumed value of the spread rate. Hence to compute two spread rates for two assumed spread rates, and then to verify a result by predicting a spread rate for the inferred equilibrium value took between 12 days and three weeks each. If this model is to be used to prepare tables of results for interpolation, either a much more powerful computer or a very long time will be needed.

Appendix A provides an estimate of the number of model predictions that would be needed to create a set of tables from which crown fire spread rate predictions could be interpolated. The number of entries required in the tables, each entry representing a model prediction, is estimated to be between 270 and 2700, depending upon the number of surface fuel descriptions to be considered. The number of table entries might be reduced by about a factor of 5 if a wind speed response can be formulated as a multiplying factor in the form of a polynomial based on wind speed at crown top height. But the potential reduction of a factor of 10 in model exercises is available by ignoring the surface fuel layer entirely. These possibilities might profitably be explored before establishing a fixed procedure for estimating crown fire spread rate in a landscape scale fire growth simulation.

Calculation of maximum spotting distances from hypothetical crown fires using a recent model [Albini 1998] indicate that if the fire advances through continuous crown fuel, the main fire can be expected to overrun spot fires before they can become new crown fires, if the spot fires take 20 minutes or more to develop into new crown fires. This finding implies that except for spotting over fuel breaks, tracking the edge of a growing crown fire should not require consideration of spotting. This conclusion must be considered preliminary without field confirmation, however.

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Figure 1. Inferred distribution of jack pine foliage in test plot A.

Figure 2. Cumulative distribution of jack pine foliage shown in figure 1. Natural bounds for the putative crown layer would be at 10% and 90% heights of the cumulative distribution of the overstory foliage.

Figure 3. Inferred distribution of black spruce foliage in test plot A.

Figure 4. Cumulative distribution of black spruce foliage shown in figure 3. Note that the populations of jack pine and black spruce foliage for this plot are in essentially distinct layers.

Figure 5. Inferred distribution of jack pine foliage in plot 5.

Figure 6. Ignition interface shapes predicted for the five experimental fires conducted during the International Crown Fire Modeling Experiment, Northwest Territories, Canada, 1997 - 98.

Figure 7. Spread rate increase factor variation with wind speed predicted for plot A, using a flame / burning zone radiation intensity ratio of 0.325 and burning zone effective radiometric temperature of 1250 K.

Figure 8. Spread rate increase factor variation with wind speed predicted for plot A, using a flame / burning zone radiation intensity ratio of 0.350 and burning zone effective radiometric temperature of 1250 K.

Figure 9. Spread rate increase factor variation with wind speed predicted for plot 6, using a flame / burning zone radiation intensity ratio of 0.350 and burning zone effective radiometric temperature of 1250 K.

Figure 10. Spread rate increase factor variation with wind speed predicted for plot 8, using a flame / burning zone radiation intensity ratio of 0.350 and burning zone effective radiometric temperature of 1250 K.

Figure 11. Spread rate increase factor variation with wind speed predicted for the cases shown in figures 7 - 10.

Table 1. Complete fuel descriptions for the three layers of test plot A.

Table 2. Complete fuel descriptions for the three layers of plot 5.

Table 3. Complete fuel descriptions for the three layers of plot 6.

Table 4. Complete fuel descriptions for the three layers of plot 7.

Table 5. Complete fuel descriptions for the three layers of plot 8.

Table 6. Equivalent single size class fuel layers for plot A from INPREPZ2.

Table 7. Equivalent single size class fuel layers for plot 5 from INPREPZ2.

Table 8. Equivalent single size class fuel layers for plot 6 from INPREPZ2.

Table 9. Equivalent single size class fuel layers for plot 7 from INPREPZ2.

Table 10. Equivalent single size class fuel layers for plot 8 from INPREPZ2.

Table 11. Predictions of fire spread rate and flame geometry for 1997 - 98 test fires conducted as part of the International Crown Fire Modeling Experiment, Northwest Territories, Canada.

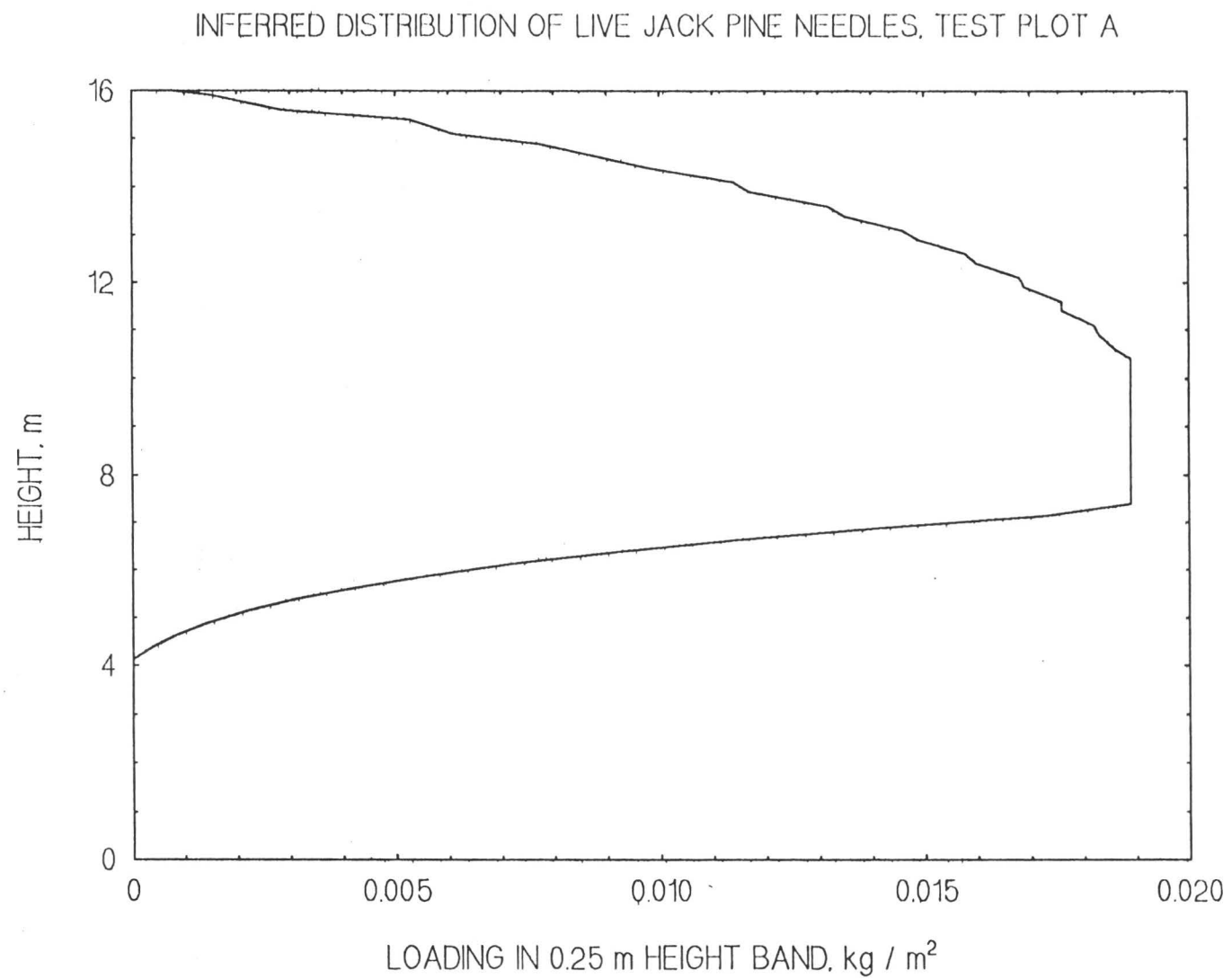


Figure 1. Inferred distribution of jack pine foliage in test plot A.

INFERRED DISTRIBUTION OF LIVE JACK PINE NEEDLES, TEST PLOT A

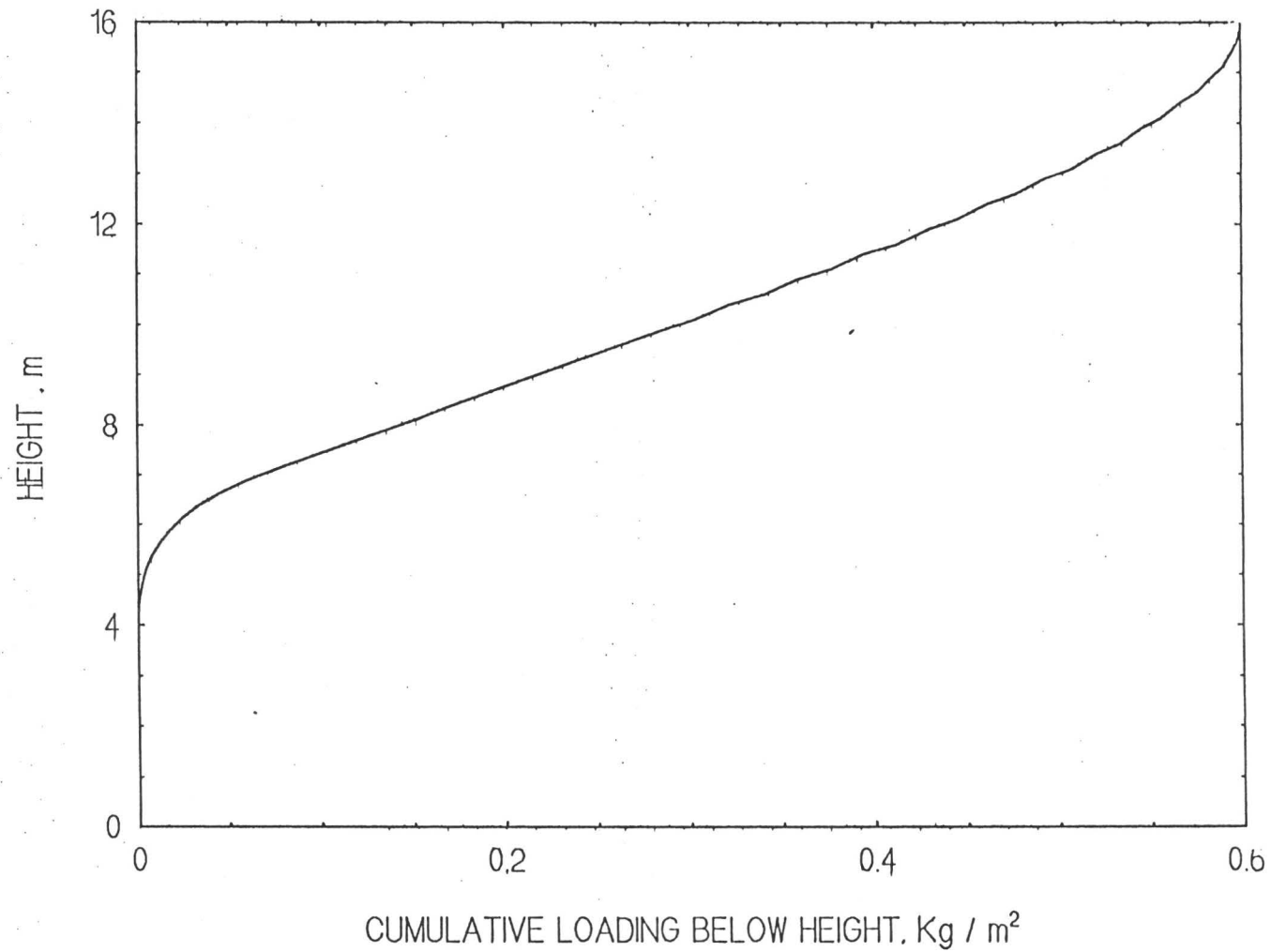


Figure 2. Cumulative distribution of jack pine foliage shown in figure 1. Natural bounds for the putative crown layer would be at 10% and 90% heights of the cumulative distribution of the overstory foliage.

INFERRED DISTRIBUTION OF LIVE BLACK SPRUCE NEEDLES, TEST PLOT A

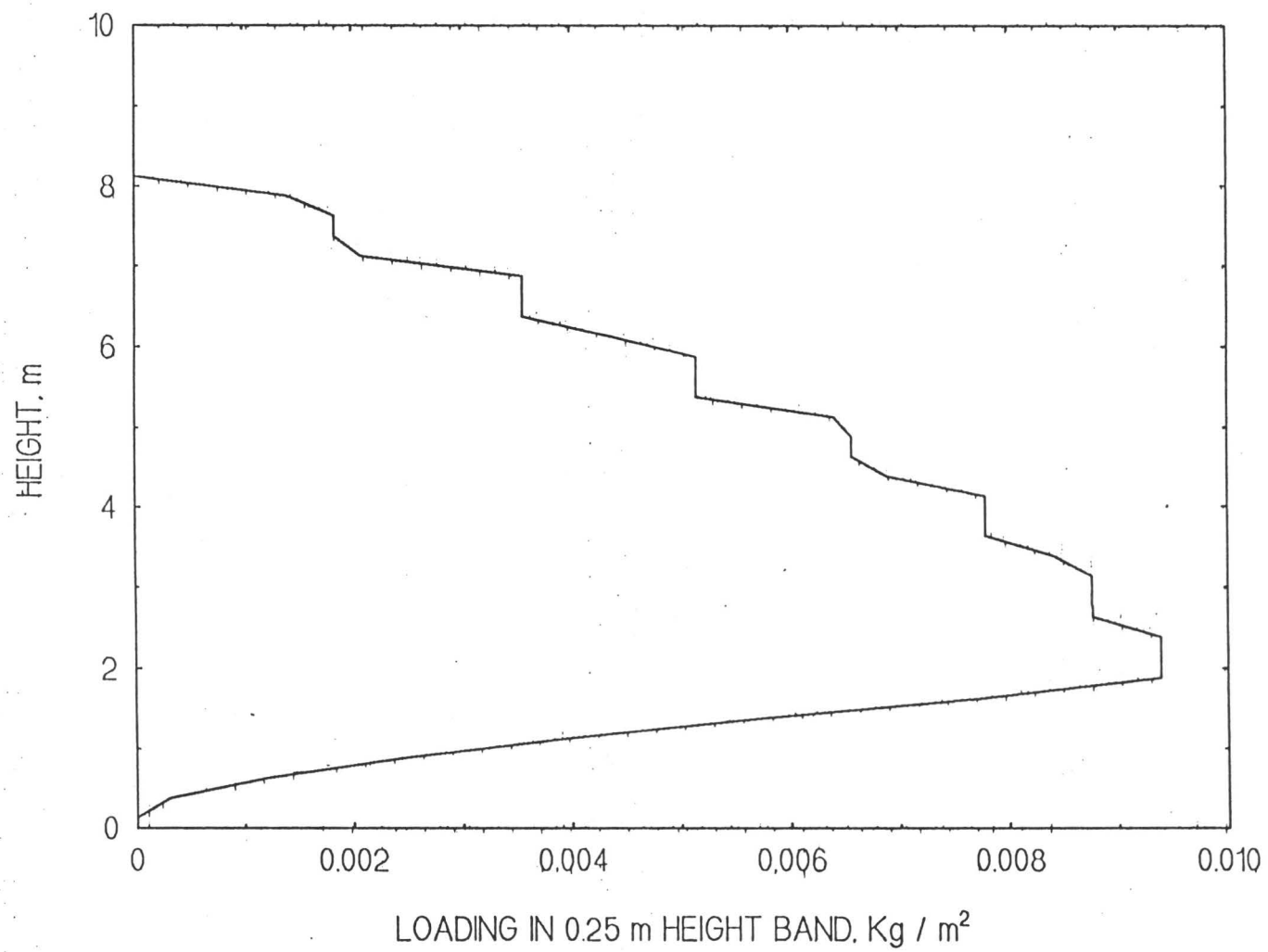


Figure 3. Inferred distribution of black spruce foliage in test plot A.

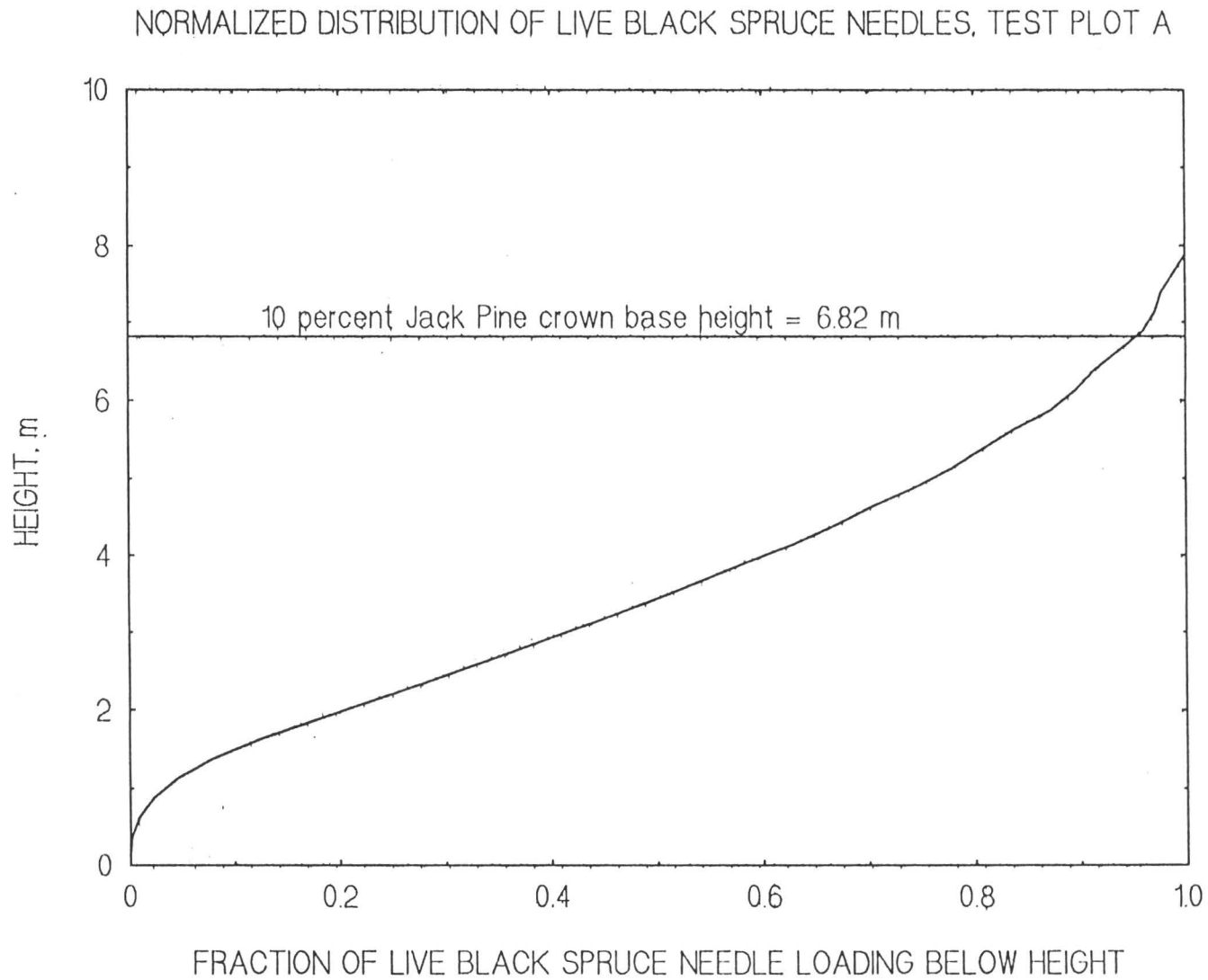


Figure 4. Cumulative distribution of black spruce foliage shown in figure 3. Note that the populations of jack pine and black spruce foliage for this plot are in essentially distinct layers.

DISTRIBUTION OF LIVE JACK PINE NEEDLES , IQFME PLOT 5

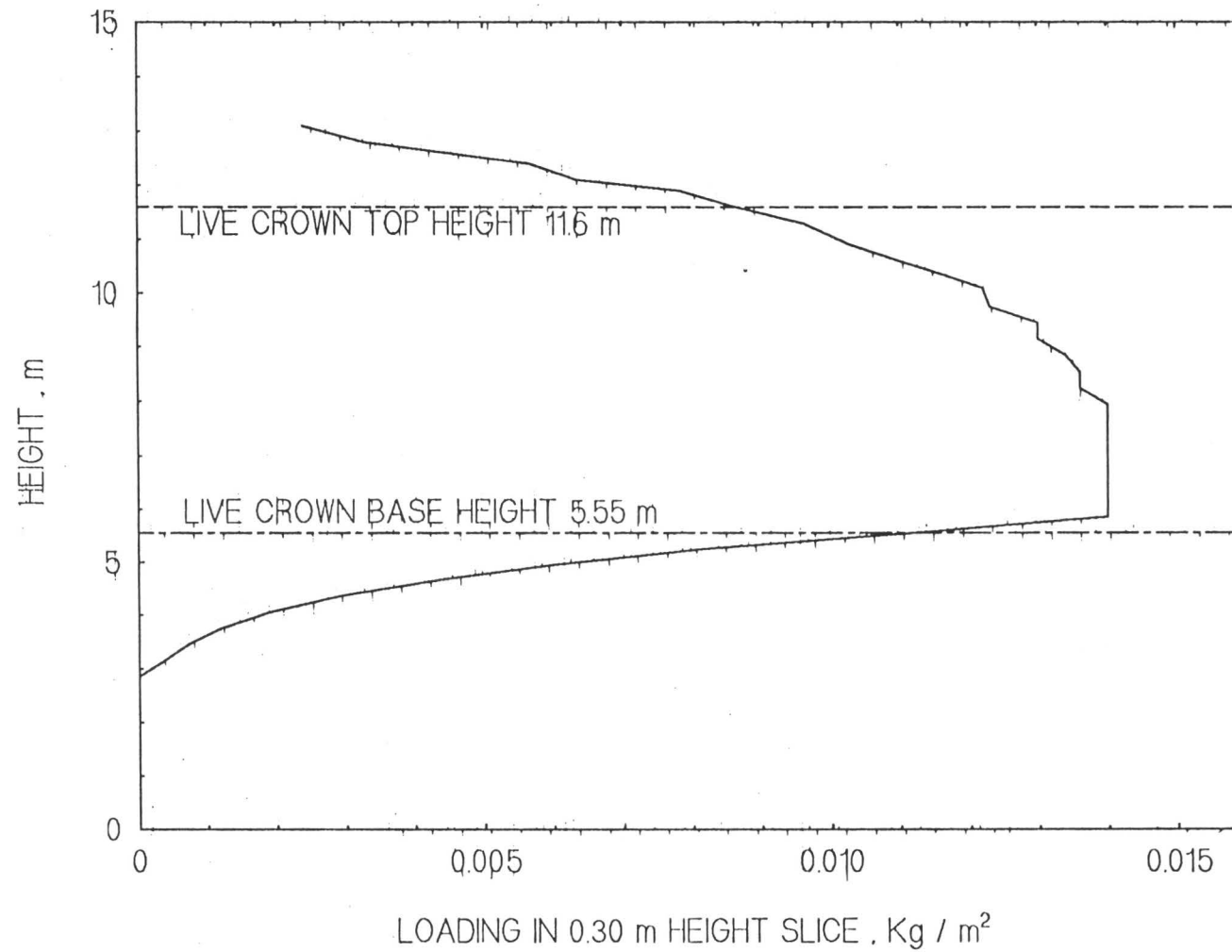


Figure 5. Inferred distribution of jack pine foliage in plot 5.

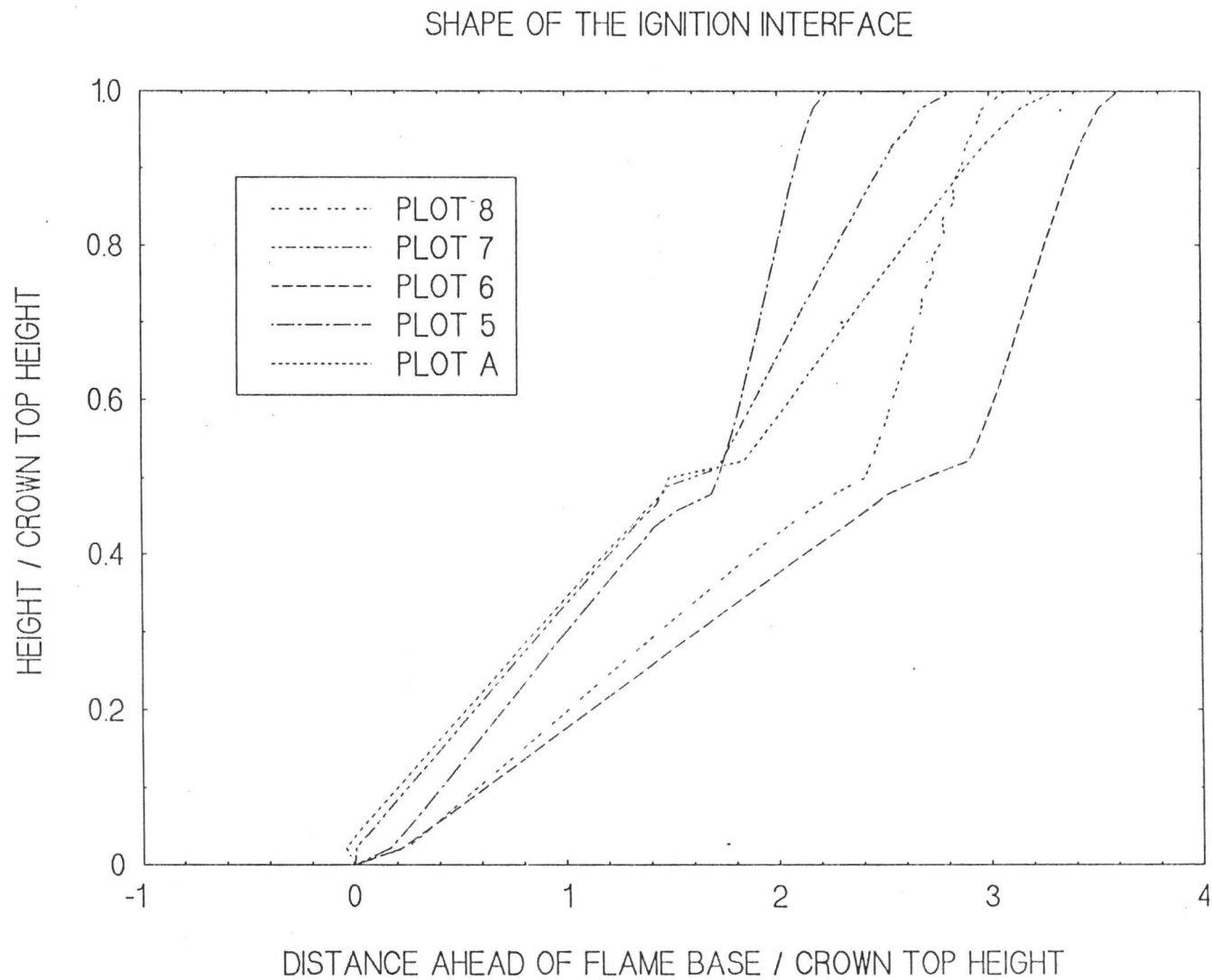


Figure 6. Ignition interface shapes predicted for the five experimental fires conducted during the International Crown Fire Modeling Experiment, Northwest Territories, Canada, 1997 - 98.

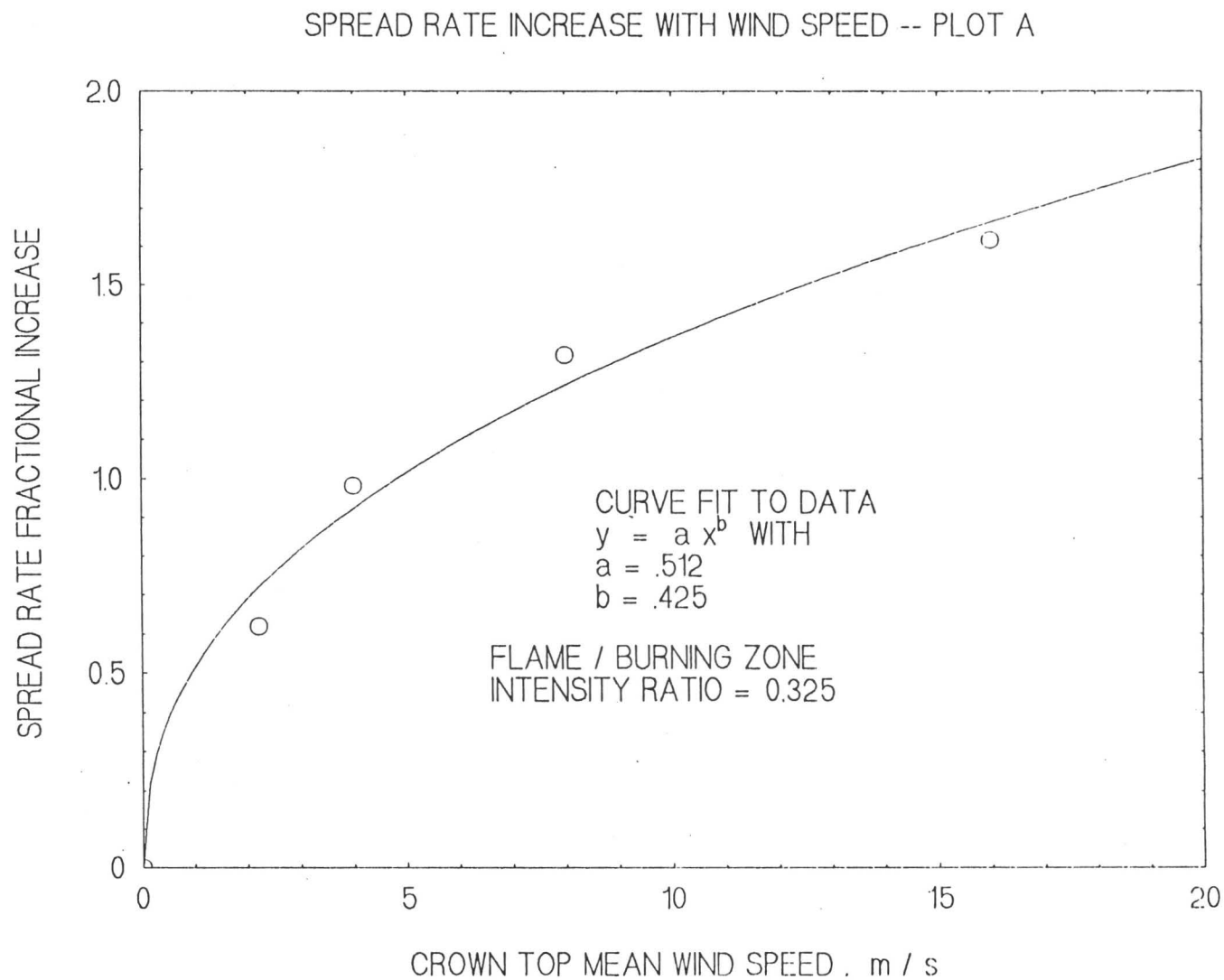


Figure 7. Spread rate increase factor variation with wind speed predicted for plot A, using a flame / burning zone radiation intensity ratio of 0.325 and burning zone effective radiometric temperature of 1250 K.

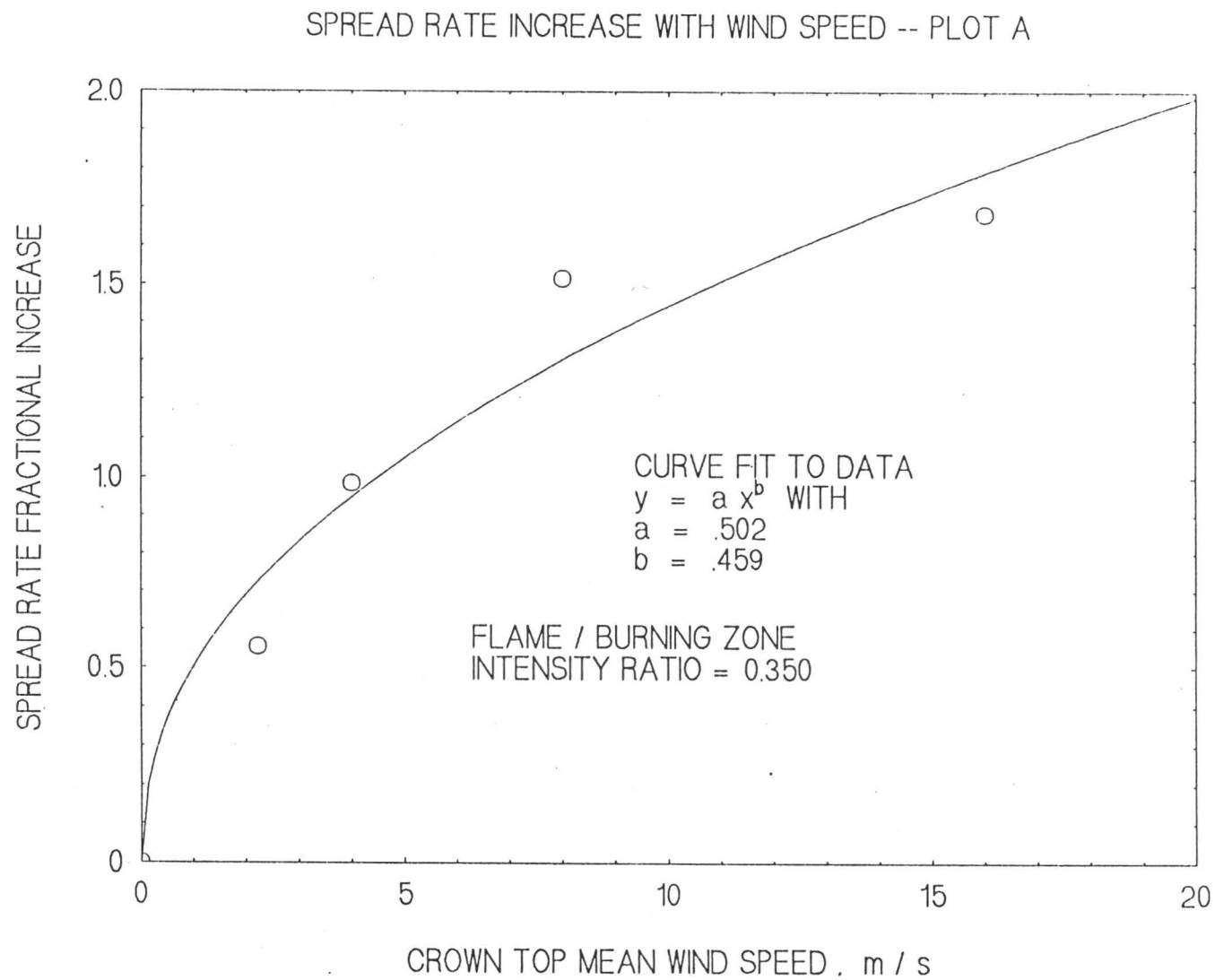


Figure 8. Spread rate increase factor variation with wind speed predicted for plot A, using a flame / burning zone radiation intensity ratio of 0.350 and burning zone effective radiometric temperature of 1250 K.

SPREAD RATE INCREASE WITH WIND SPEED -- PLOT 6

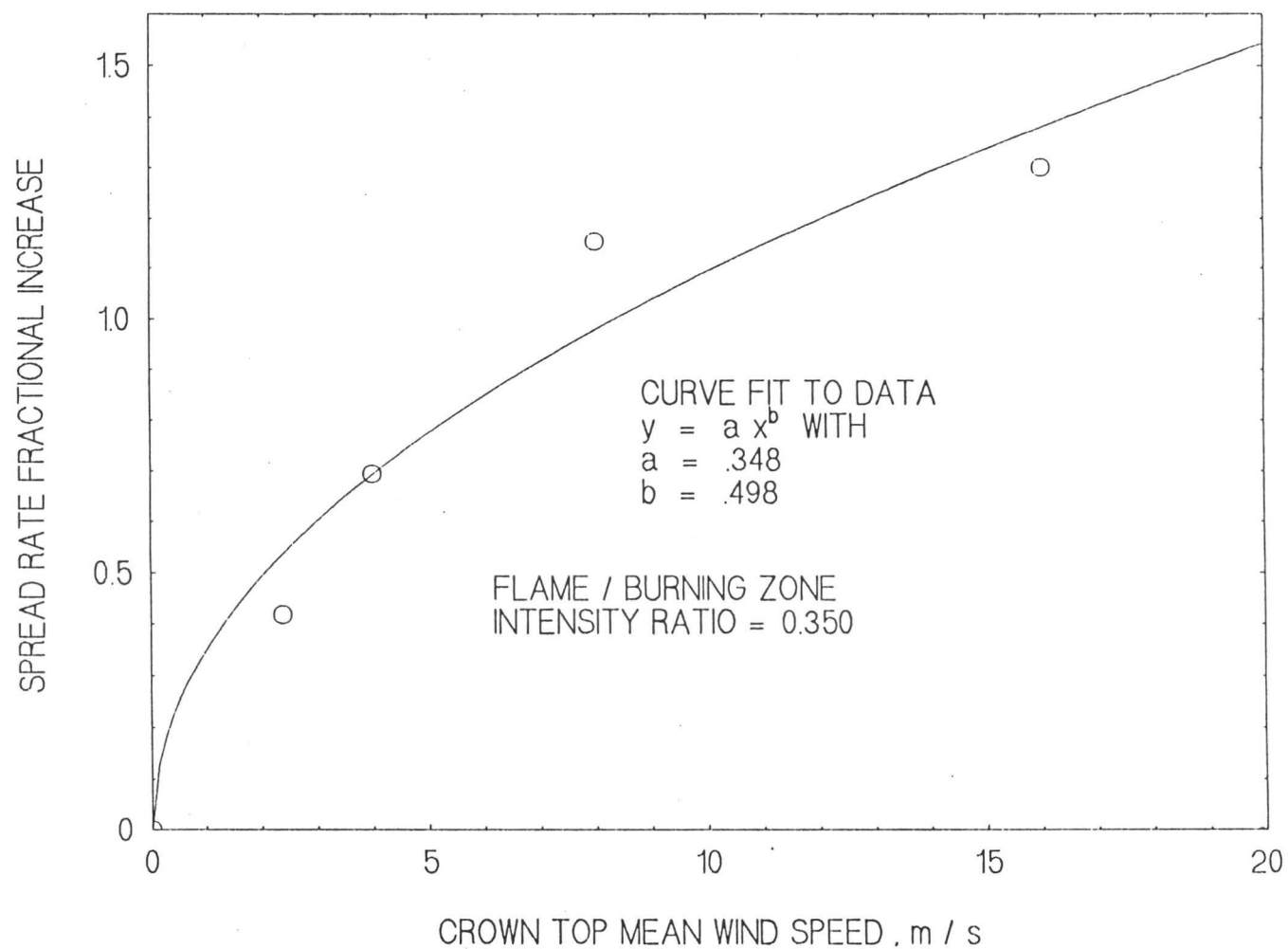


Figure 9. Spread rate increase factor variation with wind speed predicted for plot 6, using a flame / burning zone radiation intensity ratio of 0.350 and burning zone effective radiometric temperature of 1250 K.

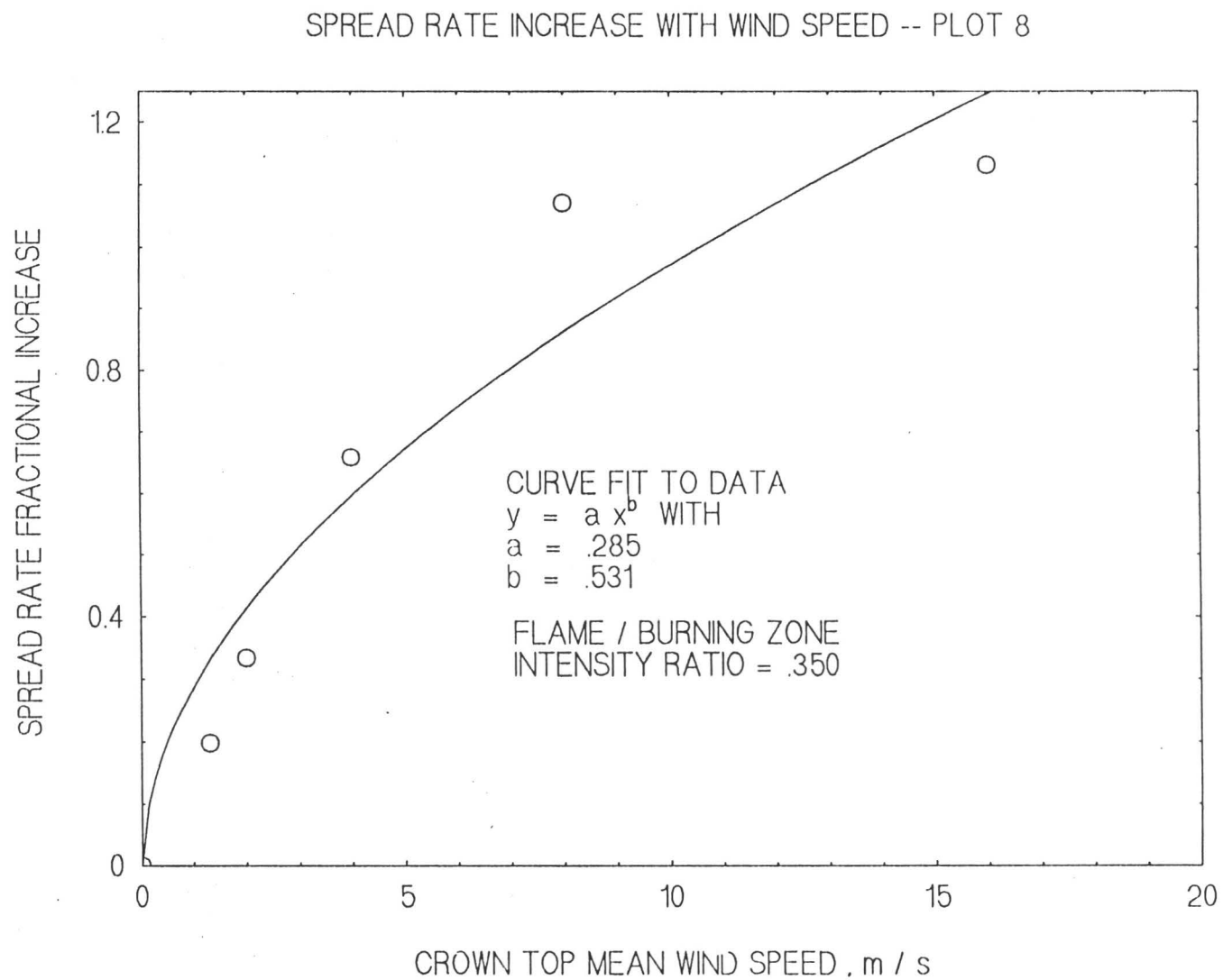


Figure 10. Spread rate increase factor variation with wind speed predicted for plot 8, using a flame / burning zone radiation intensity ratio of 0.350 and burning zone effective radiometric temperature of 1250 K.

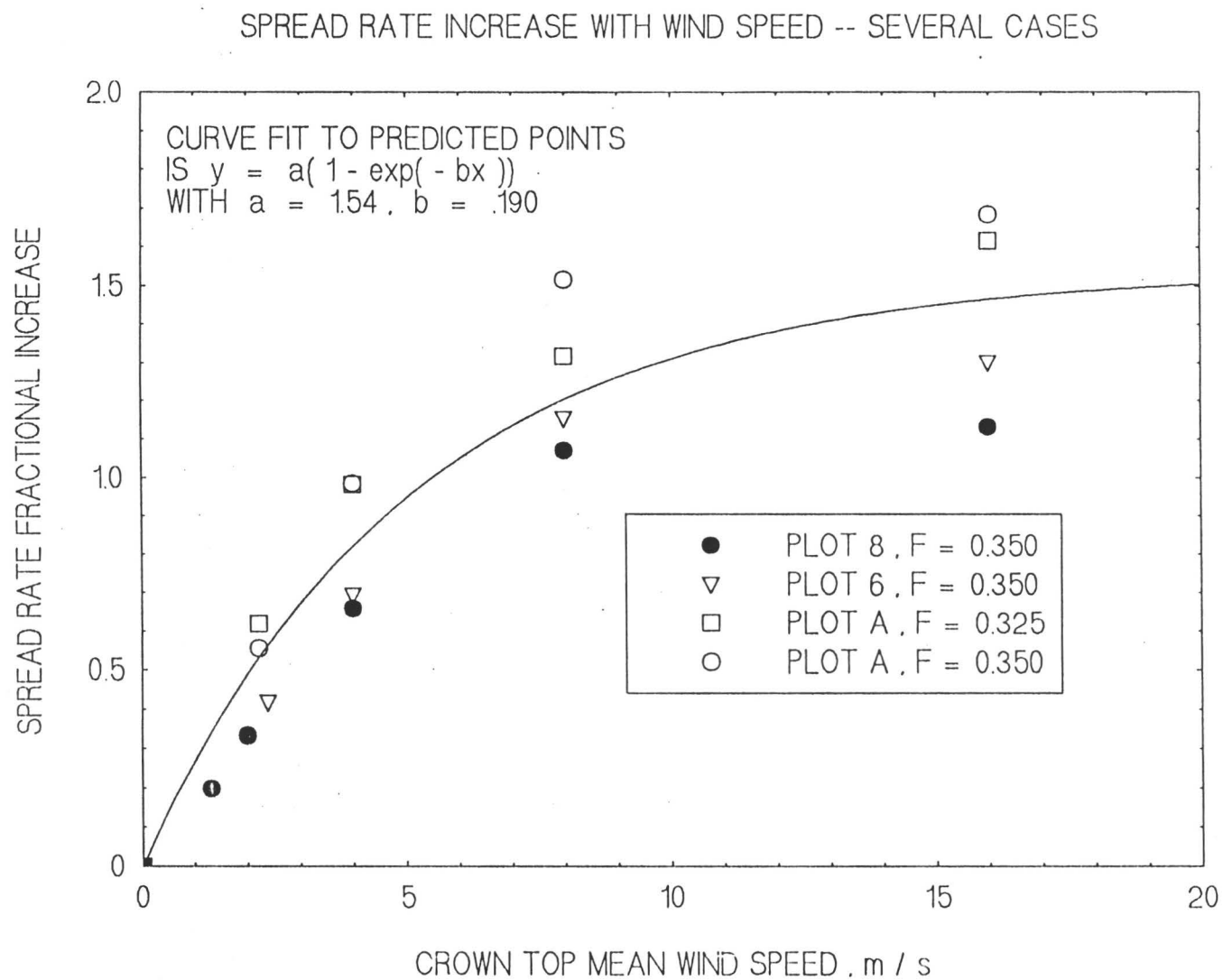


Figure 11. Spread rate increase factor variation with wind speed predicted for the cases shown in figures 7 - 10.

Table 1. Complete fuel descriptions for the three layers of test plot A.

FUEL PROPERTIES FOR INTERNATIONAL CROWN FIRE MODELING EXPERIMENT BURN PLOTS							
Component Identifier	Loading kg/m ²	Density kg/m ³	Heat cap kJ/kg K	Ash fraction	Moisture fraction	Sur/vol m ⁻¹	Ht comb kJ/kg
ICFME PLOT A SURFACE FUELS							
Ndl litter	.630E-01	.561E+03	.150E+01	.500E-01	.910E-01	.645E+04	.205E+05
Sound < .5	.126E+00	.468E+03	.150E+01	.500E-01	.860E-01	.160E+04	.190E+05
Sound .5-1	.126E-01	.506E+03	.150E+01	.500E-01	.940E-01	.533E+03	.190E+05
Sound 1-3	.674E+00	.485E+03	.150E+01	.500E-01	.880E-01	.200E+03	.190E+05
Sound 3-5	.732E+00	.475E+03	.150E+01	.500E-01	.130E+00	.100E+03	.190E+05
Sound 5-7	.885E+00	.442E+03	.150E+01	.500E-01	.130E+00	.667E+02	.190E+05
Sound 7+	.127E+01	.468E+03	.150E+01	.500E-01	.146E+00	.400E+02	.190E+05
Rotten 7+	.382E+00	.408E+03	.150E+01	.187E+00	.473E+00	.364E+02	.165E+05
ICFME TEST PLOT A STEM SPACE FUELS							
JPL < 0.5	.341E-01	.468E+03	.150E+01	.500E-01	.638E+00	.160E+04	.190E+05
JPL .5 - 1	.178E-01	.506E+03	.150E+01	.500E-01	.652E+00	.533E+03	.190E+05
JPL 1 - 3	.198E-01	.485E+03	.150E+01	.500E-01	.652E+00	.200E+03	.190E+05
JPD < 0.5	.294E+00	.468E+03	.150E+01	.500E-01	.910E-01	.160E+04	.190E+05
JPD .5 - 1	.172E+00	.506E+03	.150E+01	.500E-01	.910E-01	.533E+03	.190E+05
JPD 1 - 3	.121E+00	.485E+03	.150E+01	.500E-01	.110E+00	.200E+03	.190E+05
BSL needle	.274E+00	.561E+03	.150E+01	.500E-01	.158E+01	.543E+04	.205E+05
BSL < 0.5	.200E+00	.518E+03	.150E+01	.500E-01	.667E+00	.160E+04	.190E+05
BSL .5 - 1	.869E-01	.596E+03	.150E+01	.500E-01	.611E+00	.533E+03	.190E+05
BSL 1 - 3	.556E-02	.584E+03	.150E+01	.500E-01	.611E+00	.200E+03	.190E+05
BSD < 0.5	.524E-01	.518E+03	.150E+01	.500E-01	.115E+00	.160E+04	.190E+05
BSD .5 - 1	.166E-01	.596E+03	.150E+01	.500E-01	.195E+00	.533E+03	.190E+05
BSD 1 - 3	.136E-04	.584E+03	.150E+01	.500E-01	.195E+00	.200E+03	.190E+05
JPL 3 - 5	.671E-01	.475E+03	.150E+01	.500E-01	.650E+00	.100E+03	.190E+05
JPL 5 - 7	.323E+00	.442E+03	.150E+01	.500E-01	.650E+00	.667E+02	.190E+05
JPL 7 + cm	.961E+01	.451E+03	.150E+01	.500E-01	.650E+00	.400E+02	.190E+05
JPDb 1 - 3	.319E-01	.485E+03	.150E+01	.500E-01	.110E+00	.200E+03	.190E+05
JPDb 3 - 5	.128E+00	.475E+03	.150E+01	.500E-01	.287E+00	.100E+03	.190E+05
JPDb 5 - 7	.260E+00	.442E+03	.150E+01	.500E-01	.287E+00	.667E+02	.190E+05
JPDb 7+ cm	.765E+00	.451E+03	.150E+01	.500E-01	.390E+00	.400E+02	.190E+05
BSLb 1 - 3	.255E-01	.584E+03	.150E+01	.500E-01	.650E+00	.200E+03	.190E+05
BSLb 3 - 5	.728E-01	.493E+03	.150E+01	.500E-01	.650E+00	.100E+03	.190E+05
BSLb 5 - 7	.113E+00	.471E+03	.150E+01	.500E-01	.650E+00	.667E+02	.190E+05
BSLb 7+ cm	.217E+00	.514E+03	.150E+01	.500E-01	.650E+00	.400E+02	.190E+05
ICFME TEST PLOT A CROWN LAYER FUELS							
JP needles	.600E+00	.561E+03	.150E+01	.500E-01	.124E+01	.645E+04	.205E+05
JPL < 0.5	.215E+00	.468E+03	.150E+01	.500E-01	.638E+00	.160E+04	.190E+05
JPL .5 - 1	.120E+00	.506E+03	.150E+01	.500E-01	.652E+00	.533E+03	.190E+05
JPL 1 - 3	.204E+00	.485E+03	.150E+01	.500E-01	.650E+00	.200E+03	.190E+05
JPD < 0.5	.111E-01	.468E+03	.150E+01	.500E-01	.910E-01	.160E+04	.190E+05
JPD .5 - 1	.551E-02	.506E+03	.150E+01	.500E-01	.910E-01	.533E+03	.190E+05
JPD 1 - 3	.275E-02	.485E+03	.150E+01	.500E-01	.110E+00	.200E+03	.190E+05
BSL < 0.5	.386E-02	.518E+03	.150E+01	.500E-01	.667E+00	.160E+04	.190E+05
BSL .5 - 1	.216E-02	.596E+03	.150E+01	.500E-01	.611E+00	.533E+03	.190E+05
BSL 1 - 3	.625E-03	.584E+03	.150E+01	.500E-01	.650E+00	.200E+03	.190E+05
BSD < 0.5	.161E-02	.518E+03	.150E+01	.500E-01	.115E+00	.160E+04	.190E+05
BSD .5 - 1	.171E-02	.596E+03	.150E+01	.500E-01	.195E+00	.533E+03	.190E+05
BSD 1 - 3	.128E-05	.584E+03	.150E+01	.500E-01	.110E+00	.200E+03	.190E+05
JPLb 1 - 3	.795E-01	.485E+03	.150E+01	.500E-01	.650E+00	.200E+03	.190E+05
JPLb 3 - 5	.242E+00	.475E+03	.150E+01	.500E-01	.650E+00	.100E+03	.190E+05
JPLb 5 - 7	.388E+00	.442E+03	.150E+01	.500E-01	.650E+00	.667E+02	.190E+05
JPLb 7+ cm	.693E+00	.451E+03	.150E+01	.500E-01	.650E+00	.400E+02	.190E+05
JPDb 1 - 3	.214E-01	.485E+03	.150E+01	.500E-01	.110E+00	.200E+03	.190E+05
JPDb 3 - 5	.365E-01	.475E+03	.150E+01	.500E-01	.287E+00	.100E+03	.190E+05
JPDb 5 - 7	.404E-02	.442E+03	.150E+01	.500E-01	.287E+00	.667E+02	.190E+05
BSLb 1 - 3	.229E-03	.584E+03	.150E+01	.500E-01	.650E+00	.200E+03	.190E+05

Table 2. Complete fuel descriptions for the three layers of plot 5.

FUEL PROPERTIES FOR INTERNATIONAL CROWN FIRE MODELING EXPERIMENT BURN PLOTS								
Component Identifier	Loading kg/m ²	Density kg/m ³	Heat cap kJ/kg K	Ash fraction	Moisture fraction	Sur/vol m ⁻¹	Ht comb kJ/kg	
ICFME PLOT 5 SURFACE FUELS						8		
Ndl litter	.200E-01	.561E+03	.150E+01	.500E-01	.910E-01	.645E+04	.205E+05	
Sound < .5	.402E-01	.468E+03	.150E+01	.500E-01	.860E-01	.160E+04	.190E+05	
Sound .5-1	.319E-01	.506E+03	.150E+01	.500E-01	.940E-01	.533E+03	.190E+05	
Sound 1-3	.252E+00	.485E+03	.150E+01	.500E-01	.880E-01	.200E+03	.190E+05	
Sound 3-5	.359E+00	.475E+03	.150E+01	.500E-01	.130E+00	.100E+03	.190E+05	
Sound 5-7	.374E+00	.442E+03	.150E+01	.500E-01	.130E+00	.667E+02	.190E+05	
Sound 7+	.950E+00	.468E+03	.150E+01	.500E-01	.146E+00	.400E+02	.190E+05	
Rotten 7+	.388E+00	.408E+03	.150E+01	.187E+00	.473E+00	.364E+02	.165E+05	
ICFME PLOT 5 STEM SPACE FUELS						29		
JPL < 0.5	.187E+00	.468E+03	.150E+01	.500E-01	.701E+00	.160E+04	.190E+05	
JPL .5 - 1	.821E-02	.506E+03	.150E+01	.500E-01	.739E+00	.533E+03	.190E+05	
JPL 1 - 3	.351E-02	.485E+03	.150E+01	.500E-01	.739E+00	.200E+03	.190E+05	
JPD < 0.5	.203E+00	.468E+03	.150E+01	.500E-01	.800E-01	.160E+04	.190E+05	
JPD .5 - 1	.891E-01	.506E+03	.150E+01	.500E-01	.890E-01	.533E+03	.190E+05	
JPD 1 - 3	.945E-02	.485E+03	.150E+01	.500E-01	.890E-01	.200E+03	.190E+05	
BSL needle	.405E+00	.561E+03	.150E+01	.500E-01	.155E+01	.543E+04	.205E+05	
BSL < 0.5	.217E+00	.518E+03	.150E+01	.500E-01	.616E+00	.160E+04	.190E+05	
BSL .5 - 1	.922E-01	.596E+03	.150E+01	.500E-01	.697E+00	.533E+03	.190E+05	
BSL 1 - 3	.327E-02	.584E+03	.150E+01	.500E-01	.697E+00	.200E+03	.190E+05	
BSD < 0.5	.689E-01	.518E+03	.150E+01	.500E-01	.122E+00	.160E+04	.190E+05	
BSD .5 - 1	.180E-01	.596E+03	.150E+01	.500E-01	.203E+00	.533E+03	.190E+05	
BSD 1 - 3	.278E-02	.584E+03	.150E+01	.500E-01	.203E+00	.200E+03	.190E+05	
JPL 3 - 5	.300E+00	.475E+03	.150E+01	.500E-01	.739E+00	.100E+03	.190E+05	
JPL 5 - 7	.707E+00	.442E+03	.150E+01	.500E-01	.739E+00	.667E+02	.190E+05	
JPL 7 + cm	.395E+01	.451E+03	.150E+01	.500E-01	.739E+00	.400E+02	.190E+05	
JPDb 1 - 3	.802E-01	.485E+03	.150E+01	.500E-01	.880E-01	.200E+03	.190E+05	
JPDb 3 - 5	.276E+00	.475E+03	.150E+01	.500E-01	.130E+00	.100E+03	.190E+05	
JPDb 5 - 7	.534E+00	.442E+03	.150E+01	.500E-01	.130E+00	.667E+02	.190E+05	
JPDb 7+ cm	.762E+00	.451E+03	.150E+01	.500E-01	.146E+00	.400E+02	.190E+05	
BSLb 1 - 3	.119E-01	.584E+03	.150E+01	.500E-01	.697E+00	.200E+03	.190E+05	
BSLb 3 - 5	.476E-01	.493E+03	.150E+01	.500E-01	.697E+00	.100E+03	.190E+05	
BSLb 5 - 7	.791E-01	.471E+03	.150E+01	.500E-01	.697E+00	.667E+02	.190E+05	
BSLb 7+ cm	.165E+00	.514E+03	.150E+01	.500E-01	.697E+00	.400E+02	.190E+05	
JPLb 1 - 3	.356E-01	.485E+03	.150E+01	.500E-01	.739E+00	.200E+03	.190E+05	
BSDb 1 - 3	.297E-02	.584E+03	.150E+01	.500E-01	.880E-01	.200E+03	.190E+05	
BSDb 3 - 5	.117E-01	.493E+03	.150E+01	.500E-01	.130E+00	.100E+03	.190E+05	
BSDb 5 - 7	.262E-01	.471E+03	.150E+01	.500E-01	.130E+00	.667E+02	.190E+05	
BSDb 7+ cm	.122E+00	.514E+03	.150E+01	.500E-01	.146E+00	.400E+02	.190E+05	
ICFME PLOT 5 CROWN LAYER FUELS						25		
JP needles	.316E+00	.561E+03	.150E+01	.500E-01	.115E+01	.645E+04	.205E+05	
JPL < 0.5	.123E+00	.468E+03	.150E+01	.500E-01	.701E+00	.160E+04	.190E+05	
JPL .5 - 1	.594E-01	.506E+03	.150E+01	.500E-01	.739E+00	.533E+03	.190E+05	
JPL 1 - 3	.428E-01	.485E+03	.150E+01	.500E-01	.739E+00	.200E+03	.190E+05	
JPD < 0.5	.214E-01	.468E+03	.150E+01	.500E-01	.800E-01	.160E+04	.190E+05	
JPD .5 - 1	.339E-02	.506E+03	.150E+01	.500E-01	.890E-01	.533E+03	.190E+05	
JPD 1 - 3	.189E-02	.485E+03	.150E+01	.500E-01	.880E-01	.200E+03	.190E+05	
BSL < 0.5	.111E-01	.518E+03	.150E+01	.500E-01	.616E+00	.160E+04	.190E+05	
BSL .5 - 1	.615E-02	.596E+03	.150E+01	.500E-01	.697E+00	.533E+03	.190E+05	
BSL 1 - 3	.169E-02	.584E+03	.150E+01	.500E-01	.697E+00	.200E+03	.190E+05	
BSD < 0.5	.105E-01	.518E+03	.150E+01	.500E-01	.122E+00	.160E+04	.190E+05	
BSD .5 - 1	.801E-02	.596E+03	.150E+01	.500E-01	.203E+00	.533E+03	.190E+05	
BSD 1 - 3	.187E-02	.584E+03	.150E+01	.500E-01	.880E-01	.200E+03	.190E+05	
JPLb 1 - 3	.728E-01	.584E+03	.150E+01	.500E-01	.739E+00	.200E+03	.190E+05	
JPLb 3 - 5	.273E+00	.493E+03	.150E+01	.500E-01	.739E+00	.100E+03	.190E+05	
JPLb 5 - 7	.325E+00	.471E+03	.150E+01	.500E-01	.739E+00	.667E+02	.190E+05	

FUEL PROPERTIES FOR INTERNATIONAL CROWN FIRE MODELING EXPERIMENT BURN PLOTS							
Component Identifier	Loading kg/m ²	Density kg/m ³	Heat cap kJ/kg K	Ash fraction	Moisture fraction	Sur/vol m ⁻¹	Ht comb kJ/kg
ICFME PLOT 6 SURFACE FUELS					8		
Ndl litter	.173E-01	.561E+03	.150E+01	.500E-01	.143E+00	.645E+04	.205E+05
Sound < .5	.346E-01	.468E+03	.150E+01	.500E-01	.120E+00	.160E+04	.190E+05
Sound .5-1	.317E-01	.506E+03	.150E+01	.500E-01	.141E+00	.533E+03	.190E+05
Sound 1-3	.182E+00	.485E+03	.150E+01	.500E-01	.160E+00	.200E+03	.190E+05
Sound 3-5	.240E+00	.475E+03	.150E+01	.500E-01	.137E+00	.100E+03	.190E+05
Sound 5-7	.395E+00	.442E+03	.150E+01	.500E-01	.137E+00	.667E+02	.190E+05
Sound 7+	.289E+00	.468E+03	.150E+01	.500E-01	.150E+00	.400E+02	.190E+05
Rotten 7+	.175E+00	.408E+03	.150E+01	.187E+00	.668E+00	.364E+02	.165E+05
ICFME PLOT 6 STEM SPACE FUELS					29		
JPL < 0.5	.141E-01	.468E+03	.150E+01	.500E-01	.555E+00	.160E+04	.190E+05
JPL .5 - 1	.642E-02	.506E+03	.150E+01	.500E-01	.886E+00	.533E+03	.190E+05
JPL 1 - 3	.338E-02	.485E+03	.150E+01	.500E-01	.886E+00	.200E+03	.190E+05
JPD < 0.5	.155E+00	.468E+03	.150E+01	.500E-01	.114E+00	.160E+04	.190E+05
JPD .5 - 1	.738E-01	.506E+03	.150E+01	.500E-01	.120E+00	.533E+03	.190E+05
JPD 1 - 3	.123E-01	.485E+03	.150E+01	.500E-01	.160E+00	.200E+03	.190E+05
BSL needle	.736E+00	.561E+03	.150E+01	.500E-01	.155E+01	.543E+04	.205E+05
BSL < 0.5	.415E+00	.518E+03	.150E+01	.500E-01	.577E+00	.160E+04	.190E+05
BSL .5 - 1	.189E+00	.596E+03	.150E+01	.500E-01	.605E+00	.533E+03	.190E+05
BSL 1 - 3	.120E-01	.584E+03	.150E+01	.500E-01	.605E+00	.200E+03	.190E+05
BSD < 0.5	.190E+00	.518E+03	.150E+01	.500E-01	.115E+00	.160E+04	.190E+05
BSD .5 - 1	.709E-01	.596E+03	.150E+01	.500E-01	.283E+00	.533E+03	.190E+05
BSD 1 - 3	.701E-02	.584E+03	.150E+01	.500E-01	.160E+00	.200E+03	.190E+05
JPL 3 - 5	.154E+00	.475E+03	.150E+01	.500E-01	.886E+00	.100E+03	.190E+05
JPL 5 - 7	.443E+00	.442E+03	.150E+01	.500E-01	.886E+00	.667E+02	.190E+05
JPL 7 + cm	.359E+01	.451E+03	.150E+01	.500E-01	.886E+00	.400E+02	.190E+05
JPDb 1 - 3	.428E-01	.485E+03	.150E+01	.500E-01	.160E+00	.200E+03	.190E+05
JPDb 3 - 5	.154E+00	.475E+03	.150E+01	.500E-01	.137E+00	.100E+03	.190E+05
JPDb 5 - 7	.315E+00	.442E+03	.150E+01	.500E-01	.137E+00	.667E+02	.190E+05
JPDb 7+ cm	.474E+00	.451E+03	.150E+01	.500E-01	.150E+00	.400E+02	.190E+05
BSLb 1 - 3	.628E-01	.584E+03	.150E+01	.500E-01	.605E+00	.200E+03	.190E+05
BSLb 3 - 5	.232E+00	.493E+03	.150E+01	.500E-01	.605E+00	.100E+03	.190E+05
BSLb 5 - 7	.394E+00	.471E+03	.150E+01	.500E-01	.605E+00	.667E+02	.190E+05
BSLb 7+ cm	.520E+00	.514E+03	.150E+01	.500E-01	.605E+00	.400E+02	.190E+05
JPLb 1 - 3	.135E-01	.485E+03	.150E+01	.500E-01	.886E+00	.200E+03	.190E+05
BSDb 1 - 3	.152E-01	.584E+03	.150E+01	.500E-01	.160E+00	.200E+03	.190E+05
BSDb 3 - 5	.574E-01	.493E+03	.150E+01	.500E-01	.137E+00	.100E+03	.190E+05
BSDb 5 - 7	.112E+00	.471E+03	.150E+01	.500E-01	.137E+00	.667E+02	.190E+05
BSDb 7+ cm	.306E+00	.514E+03	.150E+01	.500E-01	.150E+00	.400E+02	.190E+05
ICFME PLOT 6 CROWN LAYER FUELS					25		
JP needles	.264E+00	.561E+03	.150E+01	.500E-01	.103E+01	.645E+04	.205E+05
JPL < 0.5	.101E+00	.468E+03	.150E+01	.500E-01	.555E+00	.160E+04	.190E+05
JPL .5 - 1	.509E-01	.506E+03	.150E+01	.500E-01	.886E+00	.533E+03	.190E+05
JPL 1 - 3	.469E-01	.485E+03	.150E+01	.500E-01	.886E+00	.200E+03	.190E+05
JPD < 0.5	.122E-01	.468E+03	.150E+01	.500E-01	.114E+00	.160E+04	.190E+05
JPD .5 - 1	.241E-02	.506E+03	.150E+01	.500E-01	.120E+00	.533E+03	.190E+05
JPD 1 - 3	.128E-02	.485E+03	.150E+01	.500E-01	.160E+00	.200E+03	.190E+05
BSL < 0.5	.294E-01	.518E+03	.150E+01	.500E-01	.577E+00	.160E+04	.190E+05
BSL .5 - 1	.161E-01	.596E+03	.150E+01	.500E-01	.605E+00	.533E+03	.190E+05
BSL 1 - 3	.346E-02	.584E+03	.150E+01	.500E-01	.605E+00	.200E+03	.190E+05
BSD < 0.5	.259E-01	.518E+03	.150E+01	.500E-01	.115E+00	.160E+04	.190E+05
BSD .5 - 1	.179E-01	.596E+03	.150E+01	.500E-01	.283E+00	.533E+03	.190E+05
BSD 1 - 3	.290E-02	.584E+03	.150E+01	.500E-01	.160E+00	.200E+03	.190E+05
JPLb 1 - 3	.728E-01	.485E+03	.150E+01	.500E-01	.886E+00	.200E+03	.190E+05
JPLb 3 - 5	.194E+00	.475E+03	.150E+01	.500E-01	.886E+00	.100E+03	.190E+05
JPLb 5 - 7	.246E+00	.442E+03	.150E+01	.500E-01	.886E+00	.667E+02	.190E+05

Table 4. Complete fuel descriptions for the three layers of plot 7.

FUEL PROPERTIES FOR INTERNATIONAL CROWN FIRE MODELING EXPERIMENT BURN PLOTS							
Component Identifier	Loading kg/m ²	Density kg/m ³	Heat cap kJ/kg K	Ash fraction	Moisture fraction	Sur/vol m ⁻¹	Ht comb kJ/kg
ICFME PLOT 7 SURFACE FUELS					8		
Ndl litter	.199E-01	.561E+03	.150E+01	.500E-01	.740E-01	.645E+04	.205E+05
Sound < .5	.397E-01	.468E+03	.150E+01	.500E-01	.580E-01	.160E+04	.190E+05
Sound .5-1	.314E-01	.506E+03	.150E+01	.500E-01	.680E-01	.533E+03	.190E+05
Sound 1-3	.174E+00	.485E+03	.150E+01	.500E-01	.770E-01	.200E+03	.190E+05
Sound 3-5	.180E+00	.475E+03	.150E+01	.500E-01	.104E+00	.100E+03	.190E+05
Sound 5-7	.186E+00	.442E+03	.150E+01	.500E-01	.104E+00	.667E+02	.190E+05
Sound 7+	.230E+00	.468E+03	.150E+01	.500E-01	.219E+00	.400E+02	.190E+05
Rotten 7+	.105E+00	.408E+03	.150E+01	.187E+00	.540E+00	.364E+02	.165E+05
ICFME PLOT 7 STEM SPACE FUELS					29		
JPL < 0.5	.333E-01	.468E+03	.150E+01	.500E-01	.715E+00	.160E+04	.190E+05
JPL .5 - 1	.642E-02	.506E+03	.150E+01	.500E-01	.799E+00	.533E+03	.190E+05
JPL 1 - 3	.116E-01	.485E+03	.150E+01	.500E-01	.799E+00	.200E+03	.190E+05
JPD < 0.5	.279E+00	.468E+03	.150E+01	.500E-01	.670E-01	.160E+04	.190E+05
JPD .5 - 1	.144E+00	.506E+03	.150E+01	.500E-01	.760E-01	.533E+03	.190E+05
JPD 1 - 3	.442E-01	.485E+03	.150E+01	.500E-01	.770E-01	.200E+03	.190E+05
BSL needle	.426E+00	.561E+03	.150E+01	.500E-01	.117E+01	.543E+04	.205E+05
BSL < 0.5	.256E+00	.518E+03	.150E+01	.500E-01	.562E+00	.160E+04	.190E+05
BSL .5 - 1	.115E+00	.596E+03	.150E+01	.500E-01	.628E+00	.533E+03	.190E+05
BSL 1 - 3	.756E-02	.584E+03	.150E+01	.500E-01	.628E+00	.200E+03	.190E+05
BSD < 0.5	.812E-01	.518E+03	.150E+01	.500E-01	.880E-01	.160E+04	.190E+05
BSD .5 - 1	.271E-01	.596E+03	.150E+01	.500E-01	.104E+00	.533E+03	.190E+05
BSD 1 - 3	.625E-04	.584E+03	.150E+01	.500E-01	.770E-01	.200E+03	.190E+05
JPL 3 - 5	.235E+00	.475E+03	.150E+01	.500E-01	.799E+00	.100E+03	.190E+05
JPL 5 - 7	.610E+00	.442E+03	.150E+01	.500E-01	.799E+00	.667E+02	.190E+05
JPL 7 + cm	.767E+01	.451E+03	.150E+01	.500E-01	.799E+00	.400E+02	.190E+05
JPDb 1 - 3	.619E-01	.485E+03	.150E+01	.500E-01	.770E-01	.200E+03	.190E+05
JPDb 3 - 5	.243E+00	.475E+03	.150E+01	.500E-01	.104E+00	.100E+03	.190E+05
JPDb 5 - 7	.363E+00	.442E+03	.150E+01	.500E-01	.104E+00	.667E+02	.190E+05
JPDb 7+ cm	.260E+00	.451E+03	.150E+01	.500E-01	.219E+00	.400E+02	.190E+05
BSLb 1 - 3	.406E-01	.584E+03	.150E+01	.500E-01	.628E+00	.200E+03	.190E+05
BSLb 3 - 5	.122E+00	.493E+03	.150E+01	.500E-01	.628E+00	.100E+03	.190E+05
BSLb 5 - 7	.194E+00	.471E+03	.150E+01	.500E-01	.628E+00	.667E+02	.190E+05
BSLb 7+ cm	.311E+00	.514E+03	.150E+01	.500E-01	.628E+00	.400E+02	.190E+05
JPLb 1 - 3	.316E-01	.485E+03	.150E+01	.500E-01	.799E+00	.200E+03	.190E+05
BSDb 1 - 3	.350E-02	.584E+03	.150E+01	.500E-01	.770E-01	.200E+03	.190E+05
BSDb 3 - 5	.114E-01	.493E+03	.150E+01	.500E-01	.104E+00	.100E+03	.190E+05
BSDb 5 - 7	.462E-02	.471E+03	.150E+01	.500E-01	.104E+00	.667E+02	.190E+05
BSDb 7+ cm	.100E-05	.514E+03	.150E+01	.500E-01	.219E+00	.400E+02	.190E+05
ICFME PLOT 7 CROWN LAYER FUELS					25		
JP needles	.523E+00	.561E+03	.150E+01	.500E-01	.107E+01	.645E+04	.205E+05
JPL < 0.5	.187E+00	.468E+03	.150E+01	.500E-01	.715E+00	.160E+04	.190E+05
JPL .5 - 1	.986E-01	.506E+03	.150E+01	.500E-01	.799E+00	.533E+03	.190E+05
JPL 1 - 3	.119E+00	.485E+03	.150E+01	.500E-01	.799E+00	.200E+03	.190E+05
JPD < 0.5	.842E-02	.468E+03	.150E+01	.500E-01	.670E-01	.160E+04	.190E+05
JPD .5 - 1	.742E-03	.506E+03	.150E+01	.500E-01	.760E-01	.533E+03	.190E+05
JPD 1 - 3	.441E-03	.485E+03	.150E+01	.500E-01	.770E-01	.200E+03	.190E+05
BSL < 0.5	.101E-01	.518E+03	.150E+01	.500E-01	.562E+00	.160E+04	.190E+05
BSL .5 - 1	.557E-02	.596E+03	.150E+01	.500E-01	.628E+00	.533E+03	.190E+05
BSL 1 - 3	.137E-02	.584E+03	.150E+01	.500E-01	.628E+00	.200E+03	.190E+05
BSD < 0.5	.419E-02	.518E+03	.150E+01	.500E-01	.880E-01	.160E+04	.190E+05
BSD .5 - 1	.391E-02	.596E+03	.150E+01	.500E-01	.104E+00	.533E+03	.190E+05
BSD 1 - 3	.303E-05	.584E+03	.150E+01	.500E-01	.770E-01	.200E+03	.190E+05
JPLb 1 - 3	.108E+00	.485E+03	.150E+01	.500E-01	.799E+00	.200E+03	.190E+05
JPLb 3 - 5	.284E+00	.475E+03	.150E+01	.500E-01	.799E+00	.100E+03	.190E+05
JPLb 5 - 7	.386E+00	.442E+03	.150E+01	.500E-01	.799E+00	.667E+02	.190E+05

FUEL PROPERTIES FOR INTERNATIONAL CROWN FIRE MODELING EXPERIMENT BURN PLOTS							
Component Identifier	Loading kg/m ²	Density kg/m ³	Heat cap kJ/kg K	Ash fraction	Moisture fraction	Sur/vol m ⁻¹	Ht comb kJ/kg
ICFME PLOT 8 SURFACE FUELS					8		
Ndl litter	.193E-01	.561E+03	.150E+01	.500E-01	.107E+00	.645E+04	.205E+05
Sound < .5	.386E-01	.468E+03	.150E+01	.500E-01	.960E-01	.160E+04	.190E+05
Sound .5-1	.403E-01	.506E+03	.150E+01	.500E-01	.100E+00	.533E+03	.190E+05
Sound 1-3	.176E+00	.485E+03	.150E+01	.500E-01	.159E+00	.200E+03	.190E+05
Sound 3-5	.302E+00	.475E+03	.150E+01	.500E-01	.157E+00	.100E+03	.190E+05
Sound 5-7	.384E+00	.442E+03	.150E+01	.500E-01	.157E+00	.667E+02	.190E+05
Sound 7+	.452E+00	.468E+03	.150E+01	.500E-01	.172E+00	.400E+02	.190E+05
Rotten 7+	.158E+00	.408E+03	.150E+01	.187E+00	.528E+00	.364E+02	.165E+05
ICFME PLOT 8 STEM SPACE FUELS					29		
JPL < 0.5	.153E-01	.468E+03	.150E+01	.500E-01	.741E+00	.160E+04	.190E+05
JPL .5 - 1	.706E-02	.506E+03	.150E+01	.500E-01	.904E+00	.533E+03	.190E+05
JPL 1 - 3	.433E-02	.485E+03	.150E+01	.500E-01	.904E+00	.200E+03	.190E+05
JPD < 0.5	.139E+00	.468E+03	.150E+01	.500E-01	.860E-01	.160E+04	.190E+05
JPD .5 - 1	.684E-01	.506E+03	.150E+01	.500E-01	.950E-01	.533E+03	.190E+05
JPD 1 - 3	.144E-01	.485E+03	.150E+01	.500E-01	.159E+00	.200E+03	.190E+05
BSL needle	.696E+00	.561E+03	.150E+01	.500E-01	.118E+01	.543E+04	.205E+05
BSL < 0.5	.385E+00	.518E+03	.150E+01	.500E-01	.714E+00	.160E+04	.190E+05
BSL .5 - 1	.183E+00	.596E+03	.150E+01	.500E-01	.734E+00	.533E+03	.190E+05
BSL 1 - 3	.131E-01	.584E+03	.150E+01	.500E-01	.734E+00	.200E+03	.190E+05
BSD < 0.5	.153E+00	.518E+03	.150E+01	.500E-01	.141E+00	.160E+04	.190E+05
BSD .5 - 1	.536E-01	.596E+03	.150E+01	.500E-01	.145E+00	.533E+03	.190E+05
BSD 1 - 3	.104E-02	.584E+03	.150E+01	.500E-01	.159E+00	.200E+03	.190E+05
JPL 3 - 5	.141E+00	.475E+03	.150E+01	.500E-01	.734E+00	.100E+03	.190E+05
JPL 5 - 7	.351E+00	.442E+03	.150E+01	.500E-01	.734E+00	.667E+02	.190E+05
JPL 7 + cm	.338E+01	.451E+03	.150E+01	.500E-01	.734E+00	.400E+02	.190E+05
JPDb 1 - 3	.376E-01	.485E+03	.150E+01	.500E-01	.159E+00	.200E+03	.190E+05
JPDb 3 - 5	.130E+00	.475E+03	.150E+01	.500E-01	.157E+00	.100E+03	.190E+05
JPDb 5 - 7	.254E+00	.442E+03	.150E+01	.500E-01	.157E+00	.667E+02	.190E+05
JPDb 7+ cm	.502E+00	.451E+03	.150E+01	.500E-01	.171E+00	.400E+02	.190E+05
BSLb 1 - 3	.893E-01	.584E+03	.150E+01	.500E-01	.734E+00	.200E+03	.190E+05
BSLb 3 - 5	.310E+00	.493E+03	.150E+01	.500E-01	.734E+00	.100E+03	.190E+05
BSLb 5 - 7	.423E+00	.471E+03	.150E+01	.500E-01	.734E+00	.667E+02	.190E+05
BSLb 7+ cm	.513E+00	.514E+03	.150E+01	.500E-01	.734E+00	.400E+02	.190E+05
JPLb 1 - 3	.190E-01	.485E+03	.150E+01	.500E-01	.904E+00	.200E+03	.190E+05
BSDb 1 - 3	.664E-02	.584E+03	.150E+01	.500E-01	.159E+00	.200E+03	.190E+05
BSDb 3 - 5	.236E-01	.493E+03	.150E+01	.500E-01	.157E+00	.100E+03	.190E+05
BSDb 5 - 7	.340E-01	.471E+03	.150E+01	.500E-01	.157E+00	.667E+02	.190E+05
BSDb 7+ cm	.394E-01	.514E+03	.150E+01	.500E-01	.172E+00	.400E+02	.190E+05
ICFME PLOT 8 CROWN LAYER FUELS					22		
JP needles	.241E+00	.561E+03	.150E+01	.500E-01	.117E+01	.645E+04	.205E+05
JPL < 0.5	.893E-01	.468E+03	.150E+01	.500E-01	.741E+00	.160E+04	.190E+05
JPL .5 - 1	.457E-01	.506E+03	.150E+01	.500E-01	.904E+00	.533E+03	.190E+05
JPL 1 - 3	.467E-01	.485E+03	.150E+01	.500E-01	.904E+00	.200E+03	.190E+05
JPD < 0.5	.104E+00	.468E+03	.150E+01	.500E-01	.860E-01	.160E+04	.190E+05
JPD .5 - 1	.258E-02	.506E+03	.150E+01	.500E-01	.950E-01	.533E+03	.190E+05
JPD 1 - 3	.138E-02	.485E+03	.150E+01	.500E-01	.159E+00	.200E+03	.190E+05
BSL < 0.5	.206E-01	.518E+03	.150E+01	.500E-01	.714E+00	.160E+04	.190E+05
BSL .5 - 1	.113E-01	.596E+03	.150E+01	.500E-01	.734E+00	.533E+03	.190E+05
BSL 1 - 3	.218E-02	.584E+03	.150E+01	.500E-01	.734E+00	.200E+03	.190E+05
BSD < 0.5	.970E-02	.518E+03	.150E+01	.500E-01	.141E+00	.160E+04	.190E+05
BSD .5 - 1	.725E-02	.596E+03	.150E+01	.500E-01	.145E+00	.533E+03	.190E+05
BSD 1 - 3	.116E-03	.584E+03	.150E+01	.500E-01	.159E+00	.200E+03	.190E+05
JPLb 1 - 3	.566E-01	.485E+03	.150E+01	.500E-01	.904E+00	.200E+03	.190E+05
JPLb 3 - 5	.158E+00	.475E+03	.150E+01	.500E-01	.904E+00	.100E+03	.190E+05
JPLb 5 - 7	.200E+00	.442E+03	.150E+01	.500E-01	.904E+00	.667E+02	.190E+05

ICFME TEST PLOT A FUEL LAYER CONSOLIDATION USING INPREPZ2

Number of horizontal slices	47
Number of fuel layers	3
Ambient temperature	295 K
Ignition temperature	600 K
Crown top wind speed	2.22 m/s
ICFME PLOT A SURFACE FUELS	
Layer depth.	.30 m
Optical opacity parameter	.4691
Single component fuel loading	1.452 kg/m ²
Mass density	473.6 kg/m ³
Specific heat capacity	1.5 kJ/kg K
Ash fraction	.05312
Moisture fraction	.1201
Surface / volume ratio	612 m ⁻¹
Heat of combustion	2589 kJ/kg
Heat per unit volume required to:	
Raise fuel to 100 C	756.3 kJ/m ³
Desiccate fuel	2068 kJ/m ³
Ignite fuel	3716 kJ/m ³
ICFME TEST PLOT A STEM SPACE FUELS	
Layer depth	6.9 m
Optical opacity parameter	1.506
Single component fuel loading	2.129 kg/m ²
Mass density	488.2 kg/m ³
Specific heat capacity	1.5 kJ/kg K
Ash fraction	.05
Moisture fraction	.5808
Surface / volume ratio	1381 m ⁻¹
Heat of combustion	8399 kJ/kg
Heat per unit volume required to:	
Raise fuel to 100 C	94.68 kJ/m ³
Desiccate fuel	499.2 kJ/m ³
Ignite fuel	604.3 kJ/m ³
ICFME TEST PLOT A CROWN LAYER FUELS	
Layer depth	6.6 m
Optical opacity parameter	2.033
Single component fuel loading	1.161 kg/m ²
Mass density	519.4 kg/m ³
Specific heat capacity	1.5 kJ/kg K
Ash fraction	.05
Moisture fraction	.9323
Surface / volume ratio	3636 m ⁻¹
Heat of combustion	14,750 kJ/kg
Heat per unit volume required to:	
Raise fuel to 100 C	74.21 kJ/m ³
Desiccate fuel	444.5 kJ/m ³
Ignite fuel	504.4 kJ/m ³

Table 6. Equivalent single size class fuel layers for plot A from INPREPZ2

ICFME PLOT 5 FUEL LAYER CONSOLIDATION USING INPREPZ2

Number of horizontal slices	47
Number of fuel layers	3
Ambient temperature	294 K
Ignition temperature	600 K
Crown top wind speed	1.75 m/s

ICFME PLOT 5 SURFACE FUELS

Layer depth	.25 m
Optical opacity parameter	.1882
Single component fuel loading	.7006 kg/m ²
Mass density	471.4 kg/m ³
Specific heat capacity	1.5 kJ/kg K
Ash fraction	.05658
Moisture fraction	.1336
Surface / volume ratio	506.5 m ⁻¹
Heat of combustion	1913. kJ/kg
Heat per unit volume required to:	
Raise fuel to 100 C	456 kJ/m ³
Desiccate fuel	1301 kJ/m ³
Ignite fuel	2255 kJ/m ³

ICFME PLOT 5 STEM SPACE FUELS

Layer depth	5.25 m
Optical opacity parameter	1.793
Single component fuel loading	2.122 kg/m ²
Mass density	491.8 kg/m ³
Specific heat capacity	1.5 kJ/kg K
Ash fraction	.05
Moisture fraction	.6245
Surface / volume ratio	1673 m ⁻¹
Heat of combustion	10,340 kJ/kg
Heat per unit volume required to:	
Raise fuel to 100 C	131.5 kJ/m ³
Desiccate fuel	701.2 kJ/m ³
Ignite fuel	838.8 kJ/m ³

ICFME PLOT 5 CROWN LAYER FUELS

Layer depth	6.0 m
Optical opacity parameter	1.117
Single component fuel loading	.7170 kg/m ²
Mass density	527.3 kg/m ³
Specific heat capacity	1.5 kJ/kg K
Ash fraction	.05
Moisture fraction	.8036
Surface / volume ratio	3287 m ⁻¹
Heat of combustion	13,780 kJ/kg
Heat per unit volume required to:	
Raise fuel to 100 C	45.95 kJ/m ³
Desiccate fuel	262.7 kJ/m ³
Ignite fuel	303.4 kJ/m ³

Table 7. Equivalent single size class fuel layers for plot 5 from INPREPZ2

ICFME PLOT 6 FUEL LAYER CONSOLIDATION USING INPREPZ2

Number of horizontal slices	47
Number of fuel layers	3
Ambient temperature	297 K
Ignition temperature	600 K
Crown top wind speed	2.39 m/s
ICFME PLOT 6 SURFACE FUELS	
Layer depth	.30 m
Optical opacity parameter	.1440
Single component fuel loading	.4517 kg/m ²
Mass density	472.0 kg/m ³
Specific heat capacity	1.5 kJ/kg K
Ash fraction	.05359
Moisture fraction	.1571
Surface / volume ratio	601.9 m ⁻¹
Heat of combustion	2595. kJ/kg
Heat per unit volume required to:	
Raise fuel to 100 C	247.0 kJ/m ³
Desiccate fuel	781.1 kJ/m ³
Ignite fuel	1294 kJ/m ³
ICFME PLOT 6 STEM SPACE FUELS	
Layer depth	6.90 m
Optical opacity parameter	2.671
Single component fuel loading	2.516 kg/m ²
Mass density	518.2 kg/m ³
Specific heat capacity	1.5 kJ/kg K
Ash fraction	.05
Moisture fraction	.7504
Surface / volume ratio	2201 m ⁻¹
Heat of combustion	12,340 kJ/kg
Heat per unit volume required to:	
Raise fuel to 100 C	128.7 kJ/m ³
Desiccate fuel	746.1 kJ/m ³
Ignite fuel	870.3 kJ/m ³
ICFME PLOT 6 CROWN LAYER FUELS	
Layer depth	6.6 m
Optical opacity parameter	.9633
Single component fuel loading	.6198 kg/m ²
Mass density	521.1 kg/m ³
Specific heat capacity	1.5 kJ/kg K
Ash fraction	.05
Moisture fraction	.7542
Surface / volume ratio	3240 m ⁻¹
Heat of combustion	14,340 kJ/kg
Heat per unit volume required to:	
Raise fuel to 100 C	33.26 kJ/m ³
Desiccate fuel	193.1 kJ/m ³
Ignite fuel	225.1 kJ/m ³

Table 8. Equivalent single size class fuel layers for plot 6 from INPREPZ2

ICFME PLOT 7 FUEL LAYER CONSOLIDATION USING INPREPZ2

Number of horizontal slices	44
Number of fuel layers	3
Ambient temperature	302 K
Ignition temperature	600 K
Crown top wind speed	2.28 m/s
ICFME PLOT 7 SURFACE FUELS	
Layer depth	.30 m
Optical opacity parameter	.1411
Single component fuel loading	.3892 kg/m ²
Mass density	477.8 kg/m ³
Specific heat capacity	1.5 kJ/kg K
Ash fraction	.05292
Moisture fraction	.1041
Surface / volume ratio	692.8 m ⁻¹
Heat of combustion	3394. kJ/kg
Heat per unit volume required to:	
Raise fuel to 100 C	178.3 kJ/m ³
Desiccate fuel	483.1 kJ/m ³
Ignite fuel	924.9 kJ/m ³
ICFME PLOT 7 STEM SPACE FUELS	
Layer depth	6.30 m
Optical opacity parameter	1.907
Single component fuel loading	2.275 kg/m ²
Mass density	497.6 kg/m ³
Specific heat capacity	1.5 kJ/kg K
Ash fraction	.05
Moisture fraction	.5602
Surface / volume ratio	1668 m ⁻¹
Heat of combustion	9788 kJ/kg
Heat per unit volume required to:	
Raise fuel to 100 C	98.64 kJ/m ³
Desiccate fuel	555.3 kJ/m ³
Ignite fuel	678.2 kJ/m ³
ICFME PLOT 7 CROWN LAYER FUELS	
Layer depth	6.30 m
Optical opacity parameter	1.776
Single component fuel loading	.9829 kg/m ²
Mass density	521.7 kg/m ³
Specific heat capacity	1.5 kJ/kg K
Ash fraction	.05
Moisture fraction	.8949
Surface / volume ratio	3770 m ⁻¹
Heat of combustion	15,290 kJ/kg
Heat per unit volume required to:	
Raise fuel to 100 C	58.15 kJ/m ³
Desiccate fuel	373.3 kJ/m ³
Ignite fuel	426.4 kJ/m ³

Table 9. Equivalent single size class fuel layers for plot 7 from INPREPZ2

ICFME PLOT 8 FUEL LAYER CONSOLIDATION USING INPREPZ2

Number of horizontal slices	43
Number of fuel layers	3
Ambient temperature	304 K
Ignition temperature	600 K
Crown top wind speed	1.31 m/s

ICFME PLOT 8 SURFACE FUELS

Layer depth	.30 m
Optical opacity parameter	.1608
Single component fuel loading	.4942 kg/m ²
Mass density	473.2 kg/m ³
Specific heat capacity	1.5 kJ/kg K
Ash fraction	.05352
Moisture fraction	.1576
Surface / volume ratio	615.7 m ⁻¹
Heat of combustion	2695. kJ/kg
Heat per unit volume required to:	
Raise fuel to 100 C	245.6 kJ/m ³
Desiccate fuel	831.7 kJ/m ³
Ignite fuel	1393. kJ/m ³

ICFME PLOT 8 STEM SPACE FUELS

Layer depth	6.00 m
Optical opacity parameter	2.488
Single component fuel loading	2.271 kg/m ²
Mass density	518.0 kg/m ³
Specific heat capacity	1.5 kJ/kg K
Ash fraction	.05
Moisture fraction	.6931
Surface / volume ratio	2271 m ⁻¹
Heat of combustion	12,560 kJ/kg
Heat per unit volume required to:	
Raise fuel to 100 C	115.0 kJ/m ³
Desiccate fuel	707.0 kJ/m ³
Ignite fuel	836.9 kJ/m ³

ICFME PLOT 8 CROWN LAYER FUELS

Layer depth	6.30 m
Optical opacity parameter	.9337
Single component fuel loading	.6081 kg/m ²
Mass density	512.5 kg/m ³
Specific heat capacity	1.5 kJ/kg K
Ash fraction	.05
Moisture fraction	.7735
Surface / volume ratio	3148 m ⁻¹
Heat of combustion	15,440 kJ/kg
Heat per unit volume required to:	
Raise fuel to 100 C	31.57 kJ/m ³
Desiccate fuel	200.1 kJ/m ³
Ignite fuel	232.9 kJ/m ³

Table 10. Equivalent single size class fuel layers for plot 8 from INPREPZ2

Plot number	Crown top wind speed km / h	Spread rate *observed m / min	-----Model predictions-----		
			Spread rate m / min	Flame height m	Flame tilt deg
A	8.0	56	47.7	16	15
5	6.3	29	48.9	15	11
6	8.6	36	76.7	24	11
7	8.2	61	58.2	18	14
8	4.7	26/35**	62.5	20	3

* Alexander, 1999 and fire front maps by S. Taylor, Dec. 1999

** Wind direction shifted during burn.

Table 11. Predictions of fire spread rate and flame geometry for 1997 - 98 test fires conducted as part of the International Crown Fire Modeling Experiment, Northwest Territories, Canada.

APPENDIX A

Number of spread rate predictions needed for tabulation

The rate of spread of a crown fire depends upon the set of variables that describe the fuel quantity, arrangement, and condition, as well as the environmental parameters wind speed and terrain slope. The radiation driven spread rate model does not consider terrain slope, so this often-important variable cannot be addressed by the model in its current state of development. Direct use of this model to predict local spread rates for application in a landscape scale fire growth simulation would be completely impractical because of the long running time of the model. Therefore it has been proposed that the model be exercised against a range of fuel descriptions, fuel moisture conditions, and wind speeds, to create tabular data that can be interpolated to provide spread rate estimates almost immediately. The question then arises as to how many exercises of the spread rate model would be necessary to provide the minimum acceptable number of table entries.

To address this question one could examine archives of forest stand descriptive data, allometric equations, climatological records, surface fuel inventories, etc. These data, if available in sufficient quantity, should provide a representative set of fuel descriptions that could be approximated by a set of notional (typical) forest stands and a range of wind speeds and fuel moisture contents that could be imposed upon them. A problem with this approach is that the spread rate model requires that the fuel component descriptions be processed by the input preparation module to create "equivalent" single size class fuel descriptions for each fuel layer. This means that seemingly much different fuel descriptions can result in similar single size class equivalent ones. To circumvent this difficulty, the necessary set of fuel descriptions can be specified in terms of their single size class equivalents. These fuel descriptions can then be related to forest stand descriptions in descriptive terms, allowing selection of appropriate notional fuel sets readily.

The current version of the radiation driven spread rate model allows an essentially arbitrary distribution of fuel through vertical strata, but the input preparation module is limited to three uniform strata, identified as the surface fuel layer, the subcanopy stem space layer, and the live crown layer. This is thought to be a sufficient discretization of the fuel bed for present purposes. Indeed the surface fuel layer has, in the example exercises of the model to date, been inconsequential in determining the crown fire rate of spread. In the model exercises to date, the surface fuel layer has contributed at most a few percent of the total fire intensity. So, while the surface fire is crucial to crown fire ignition, its role may diminish in significance once the crown fire is established. Standard fuel models 2, 7, 8, 10, and 11 might be chosen as typical. The dead fuel moisture content might be set to 12% for dry conditions and to 5% for very dry, with live fuel set to 100%. This would result in approximately 10 sets of surface fuel conditions.

Characterization of each of the layers in terms of a single component "equivalent" fuel layer requires the specification of a set of descriptive parameters. These parameters are combined to form a smaller set of variables that are actually used in the model algorithm. The derived parameter set describes the fuel bed in terms of its optical opacity, its response to the absorption of heat, and its heat release per unit of planform area when it burns. The basic descriptors, the input quantities, consist of the amount, size, and condition of the fuel particles, and some thermodynamic properties, which may be taken to be constants:

- 1) Thickness or depth of the layer = δ , m
- 2) Particle surface to volume ratio = σ , m^{-1}
- 3) Particle dry mass density = ρ , kg / m^3
- 4) Particle loading = w , kg / m^2
- 5) Fuel moisture content = M , fraction of dry weight
- 6) Fuel ash content = α , fraction of dry weight
- 7) Fuel heat of combustion = H , kJ / kg
- 8) Fuel dry specific heat capacity = C_{po} , $\text{kJ} / \text{kg K}$
- 9) Fuel ignition temperature = T_{ig} , K

The particle dry mass density can be taken to be $500 \text{ kg} / \text{m}^3$, the ash fraction to be 0.05 , the dry specific heat capacity to be $1.5 \text{ kJ} / \text{kg K}$, and the ignition temperature to be 600 K , without significant error. The moisture content, surface to volume ratio, and heat of combustion are determined by the moisture contents of the individual live and dead components, their diameters, and their relative abundance. Typical values obtained by using INPREPZ2 with various inputs give the following typical values:

Property	Condition	Fuel layer	Value
Moisture content	Dry	Stem space	0.75
		Crown layer	0.90
	Very dry	Stem space	0.50
		Crown layer	0.70
Surface / volume ratio	Dry, Very dry	Stem space	1500
		Crown layer	4000
Heat of combustion	Dry, Very dry	Stem space	10,000
		Crown layer	15,000

Fuel loading is involved in determining the optical opacity parameter, C , for each layer. This quantity, which is the negative natural logarithm of the ratio of the intensity of sunlight leaving and entering the layer at zenith, tends to be roughly constant live layers and bounded for dead layers. For that reason, and because the opacity parameter is used directly in the computations, it is suggested that this parameter be specified directly and the loading be derived from it. For the stem space, the loading in kg / m^2 is approximately numerically equal to the opacity parameter, while for the live canopy layer, it is about 0.6 times C . The range of values for the opacity parameter is expected to be 0.5 - 2.0 for the live crown layer, increasing with depth of the layer, while for the stem space, since it contains more dead material, the range is probably 0.25 - 2.5 , with the value dependent upon the depth of the layer as well. Dense layers probably range from 1.5 - 2.5 depending upon layer thickness, while open layers range from 0.25 - 1.0 , depending upon thickness. An intermediate category would have an opacity parameter in the range 0.5 - 1.5 , depending upon thickness.

Layer depths can probably be expressed as a fraction of the canopy top height. It is suggested that live canopy layers be specified as $1/3$, $1/2$, or $2/3$ of the canopy top height, with corresponding opacity parameters of 0.5, 1.0, and 2.0. The layer depth of the subcanopy stem space would then be approximated as $2/3$, $1/2$, or $1/3$ of the canopy top height, ignoring (or accommodating) the depth of the surface layer. The corresponding opacity parameters for the subcanopy layer would be selected from the three ranges mentioned above, with the value determined by the nominal opacity of the layer. Open layers would contain little or no understory, while shade-tolerant heavily stocked understories would rank as dense, for example. From the opacity parameters, the loadings can be computed, as discussed above.

The standard fuel models listed above were processed through the INPREPZ2 program to provide consolidated, single-component fuel model equivalents. The processed fuel models afforded the parameters listed in the following table, for dry and very dry conditions. These quantities indicate that some consolidation should be possible, although a key for parameter selection has not yet been devised.

Model	Depth	Opacity	Loading	Surface/volume m^{-1}	Moisture fraction	Heat of combustion kJ / kg
2	0.305	2.56	0.95	5400	0.22	11,730
			0.98	5220	0.16	11,360
7	0.762	1.03	0.85	2420	0.16	7745
			0.89	2310	0.21	8085
8	0.610	1.17	0.82	3110	0.12	8849
				2870	0.05	8189
10	0.305	3.45	1.96	3530	0.32	10,190
			2.08	3320	0.26	10,520
11	0.305	1.07	1.74	1230	0.12	4376
				1120	0.05	4029

With this procedure for selecting fuel descriptors, only the canopy top height, wind speed, and ambient temperature are needed to complete the input list. The suggested values for canopy top height are 13, 25, and 50 m. The suggested wind speeds at 10 m height in the open are 0, 10, 20, 35, and 50 km / h. Assuming that these speeds are the same as those to be found at 10 m height above the canopy top, and using the logarithmic wind speed profile, the canopy top height wind speeds can be computed from:

$$U_c = U_{10} / (1 + \ln(1 + 28 / H_t)),$$

where U_c is the wind speed at crown top height, U_{10} the wind speed at 10 meters in the open, and H_t the canopy top height, in meters.

In all cases it is suggested that the ambient temperature simply be take to be 300 K, or 27 C. This parameter is not very influential when normal summer fire season temperature ranges are considered.

Parameters affecting crown fire spread rate	Cases	Description of conditions
Surface fuels	10	
Standard models	5	Select from 2, 7, 8, 10, or 11
Moisture content	2	5% and 12% dead, 100% live
Subcanopy / stem space	3	
Layer depths	(3)	H_t - Live crown layer depth
Opacity parameters	3	0.25 - 1.0 (open) , 0.5 - 1.5 (nominal) , and 1.5 - 2.5 (dense)
1-component moisture content	(2)	0.5 (very dry) and 0.75 (dry) – tied to crown
Live crown layer	6	
Layer depths	3	$H_t / 3$, $H_t / 2$, and $2H_t / 3$
Opacity parameters	(3)	0.5 , 1.0 , and 2.0 (keyed to layer depths)
1-component moisture content	2	0.7 (very dry) and 0.9 (dry)
Wind speed at 10 m in the open	5	0 , 10 , 20 , 35 , and 50 km / h
Stand heights (H_t)	3	13 , 25 , and 50 m
Total number of cases to tabulate	2700	

Figure 1. Inferred distribution of jack pine foliage in test plot A.

Figure 2. Cumulative distribution of jack pine foliage shown in figure 1. Natural bounds for the putative crown layer would be at 10% and 90% heights of the cumulative distribution of the overstory foliage.

Figure 3. Inferred distribution of black spruce foliage in test plot A.

Figure 4. Cumulative distribution of black spruce foliage shown in figure 3. Note that the populations of jack pine and black spruce foliage for this plot are in essentially distinct layers.

Figure 5. Inferred distribution of jack pine foliage in plot 5.

Figure 6. Ignition interface shapes predicted for the five experimental fires conducted during the International Crown Fire Modeling Experiment, Northwest Territories, Canada, 1997 - 98.

Figure 7. Spread rate increase factor variation with wind speed predicted for plot A, using a flame / burning zone radiation intensity ratio of 0.325 and burning zone effective radiometric temperature of 1250 K.

Figure 8. Spread rate increase factor variation with wind speed predicted for plot A, using a flame / burning zone radiation intensity ratio of 0.350 and burning zone effective radiometric temperature of 1250 K.

Figure 9. Spread rate increase factor variation with wind speed predicted for plot 6, using a flame / burning zone radiation intensity ratio of 0.350 and burning zone effective radiometric temperature of 1250 K.

Figure 10. Spread rate increase factor variation with wind speed predicted for plot 8, using a flame / burning zone radiation intensity ratio of 0.350 and burning zone effective radiometric temperature of 1250 K.

Figure 11. Spread rate increase factor variation with wind speed predicted for the cases shown in figures 7 - 10.

Table 1. Complete fuel descriptions for the three layers of test plot A.

Table 2. Complete fuel descriptions for the three layers of plot 5.

Table 3. Complete fuel descriptions for the three layers of plot 6.

Table 4 Complete fuel descriptions for the three layers of plot 7.

Table 5 Complete fuel descriptions for the three layers of plot 8

Table 6. Equivalent single size class fuel layers for plot A from INPREPZ2

Table 7. Equivalent single size class fuel layers for plot 5 from INPREPZ2

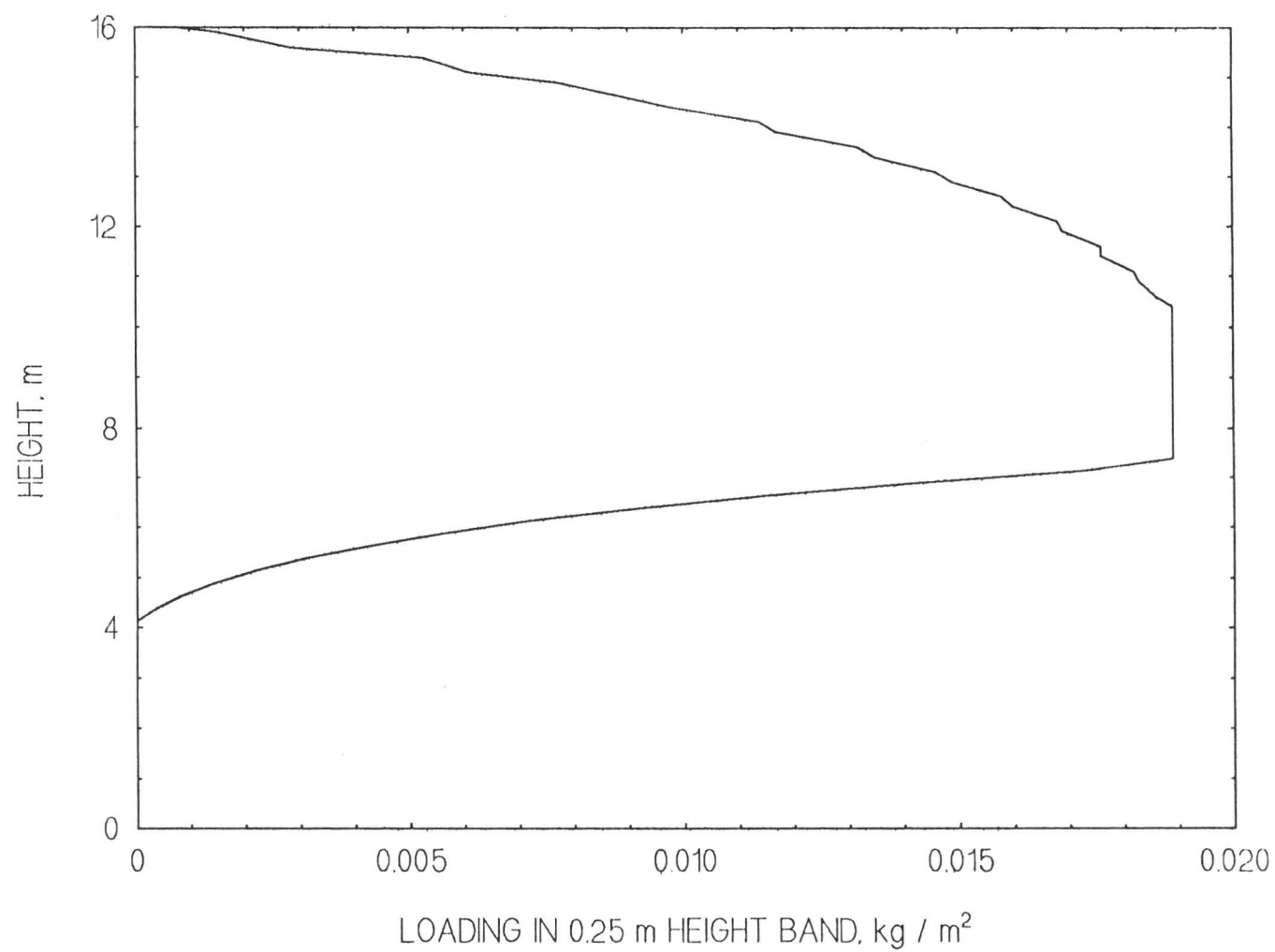
Table 8. Equivalent single size class fuel layers for plot 6 from INPREPZ2

Table 9. Equivalent single size class fuel layers for plot 7 from INPREPZ2

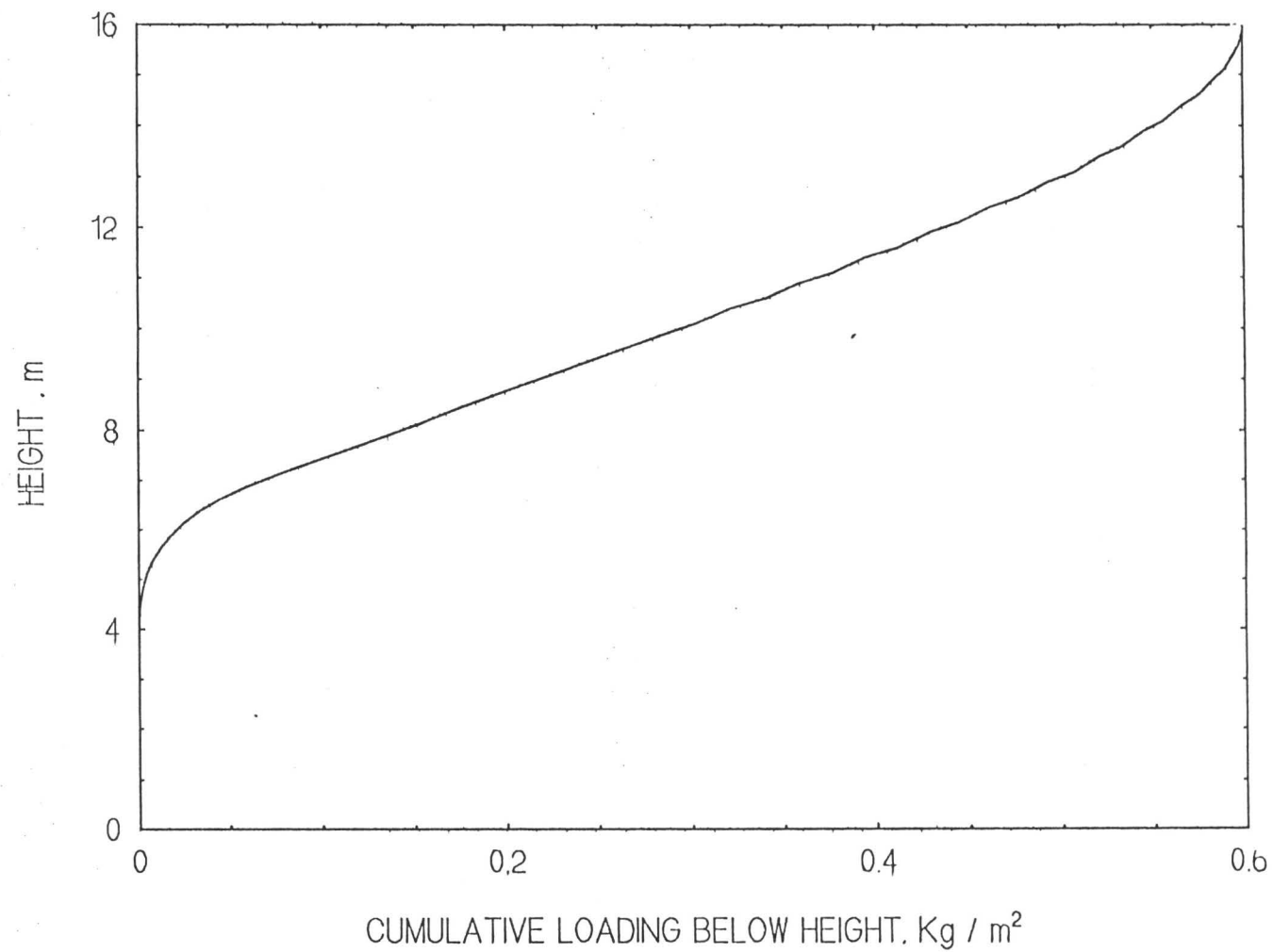
Table 10. Equivalent single size class fuel layers for plot 8 from INPREPZ2

Table 11. Predictions of fire spread rate and flame geometry for 1997 - 98 test fires conducted as part of the International Crown Fire Modeling Experiment, Northwest Territories, Canada.

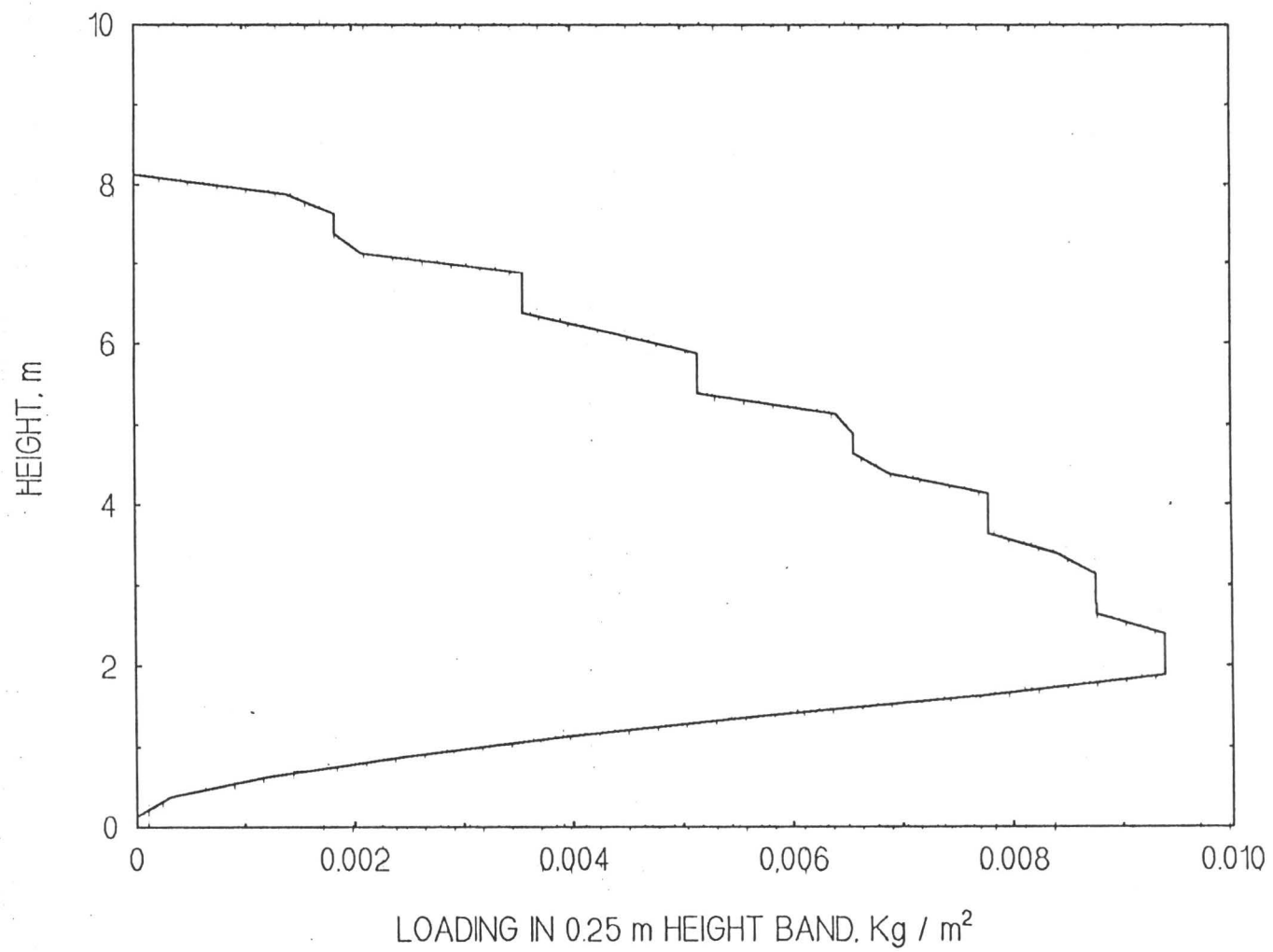
INFERRED DISTRIBUTION OF LIVE JACK PINE NEEDLES, TEST PLOT A



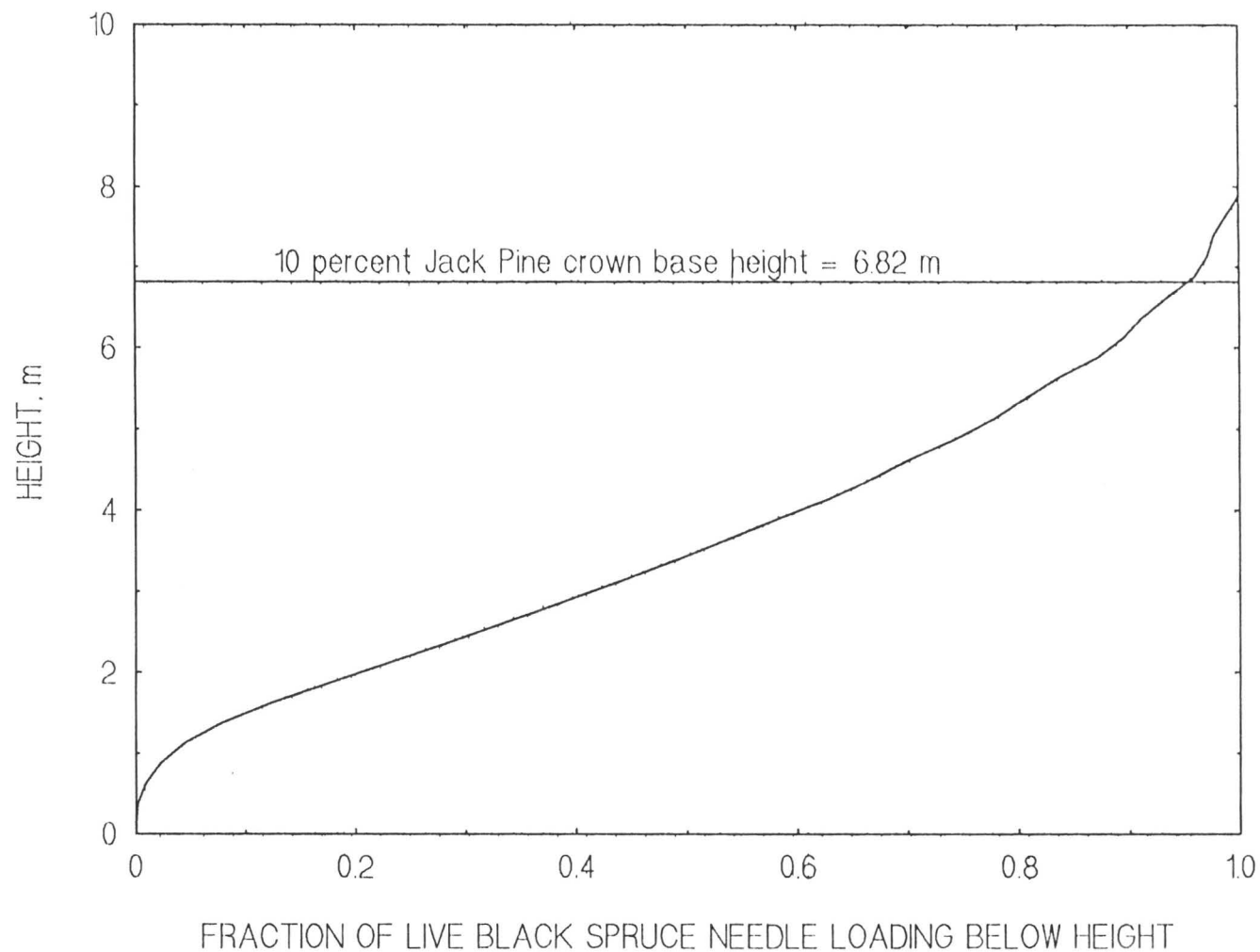
INFERRED DISTRIBUTION OF LIVE JACK PINE NEEDLES, TEST PLOT A



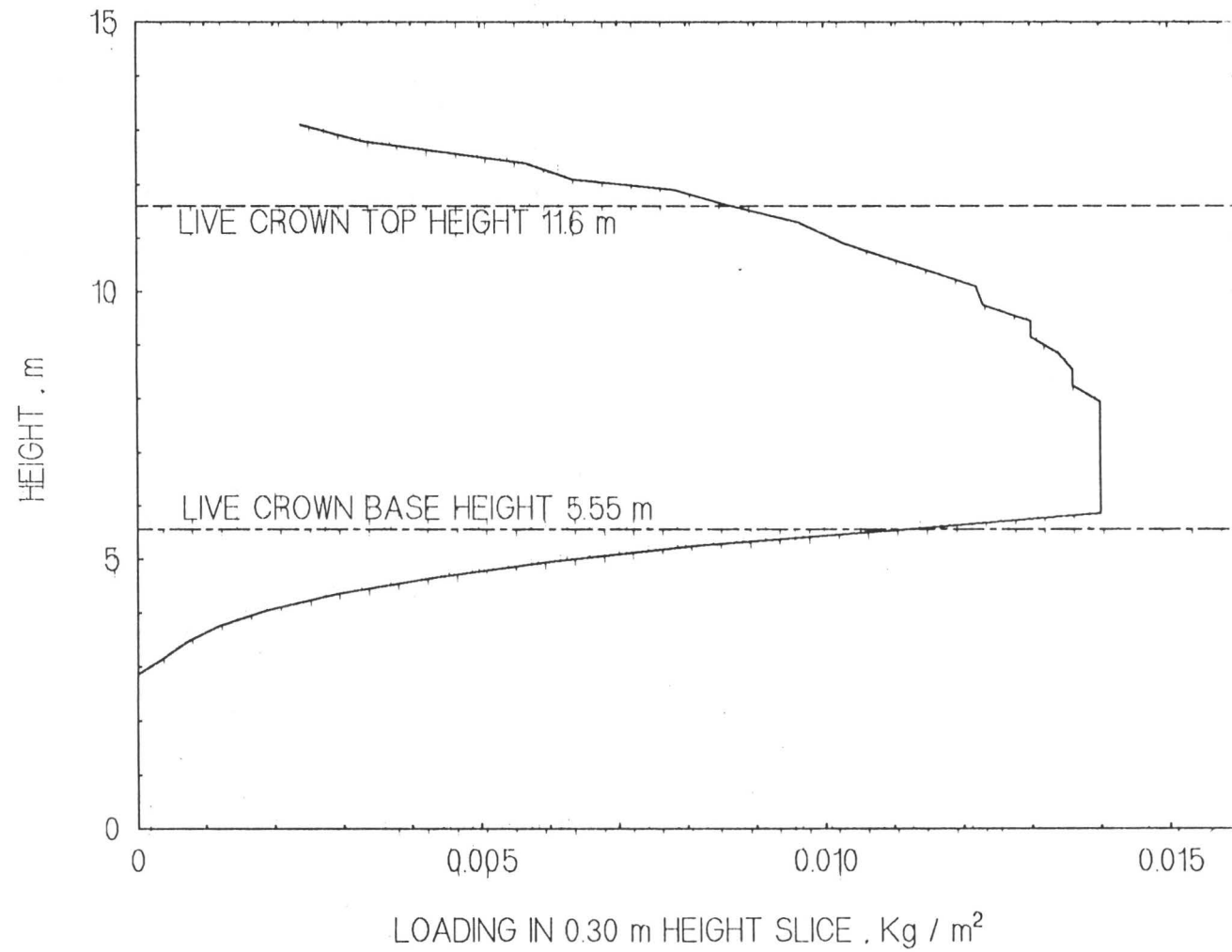
INFERRED DISTRIBUTION OF LIVE BLACK SPRUCE NEEDLES, TEST PLOT A



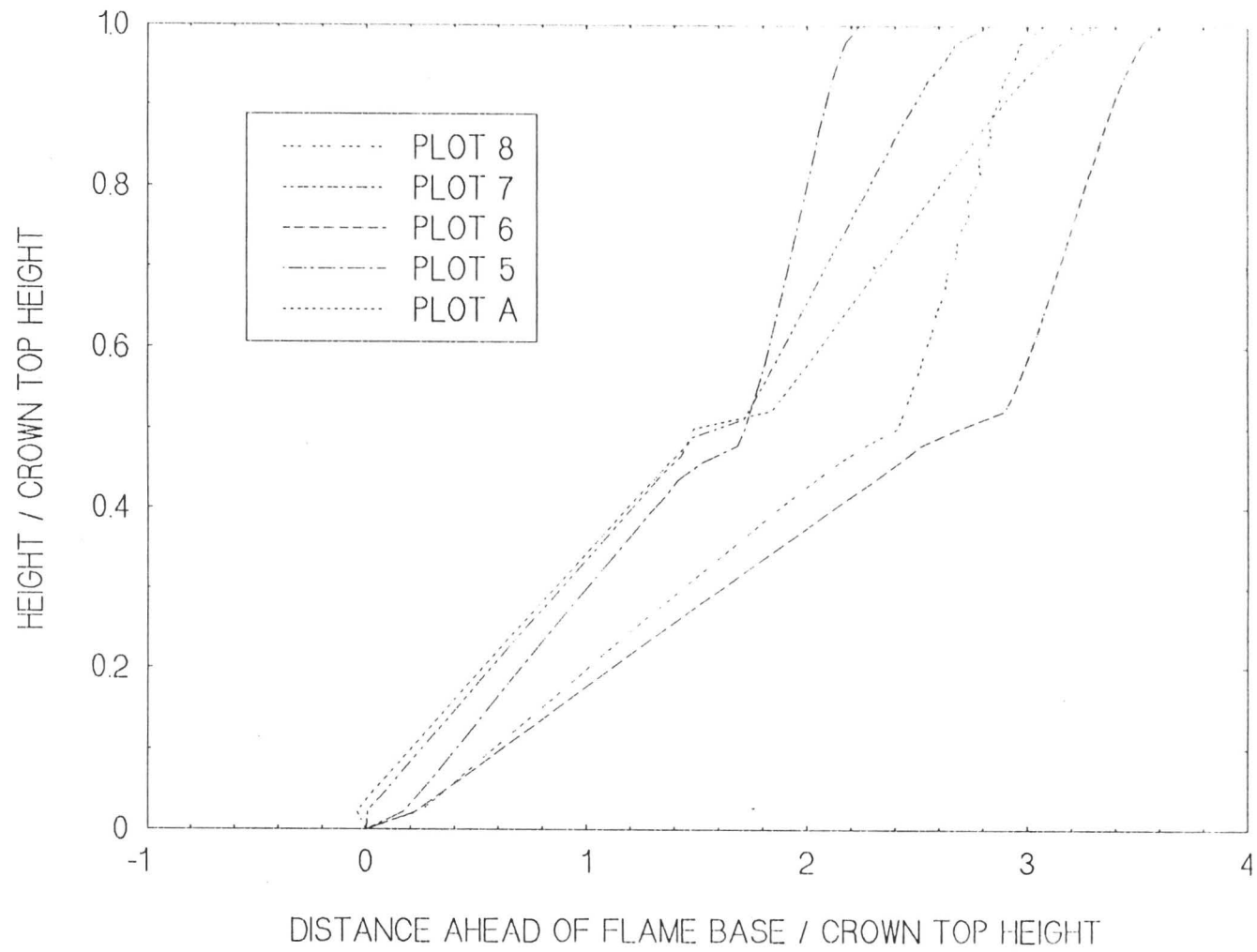
NORMALIZED DISTRIBUTION OF LIVE BLACK SPRUCE NEEDLES, TEST PLOT A



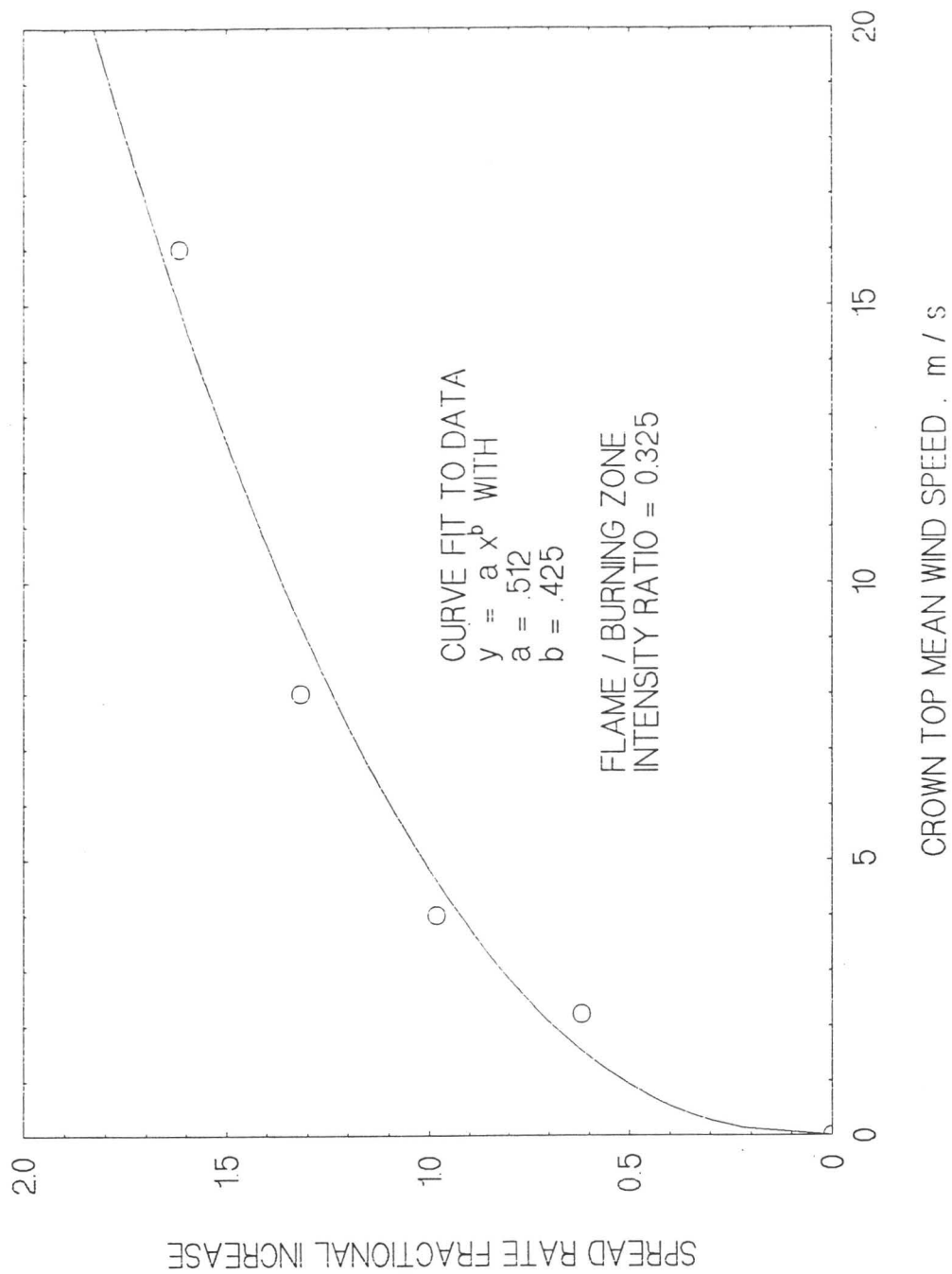
DISTRIBUTION OF LIVE JACK PINE NEEDLES . ICFME PLOT 5



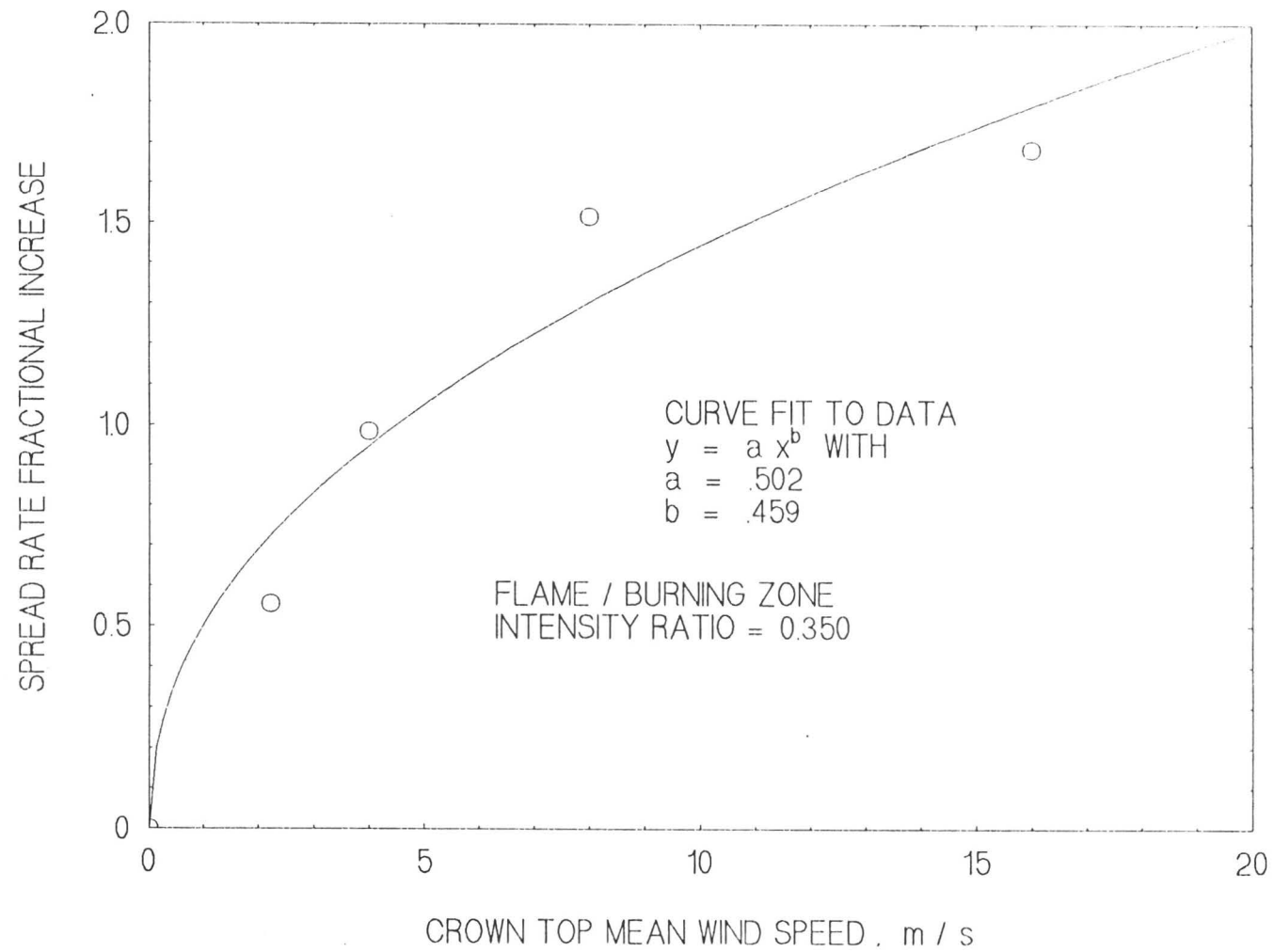
SHAPE OF THE IGNITION INTERFACE



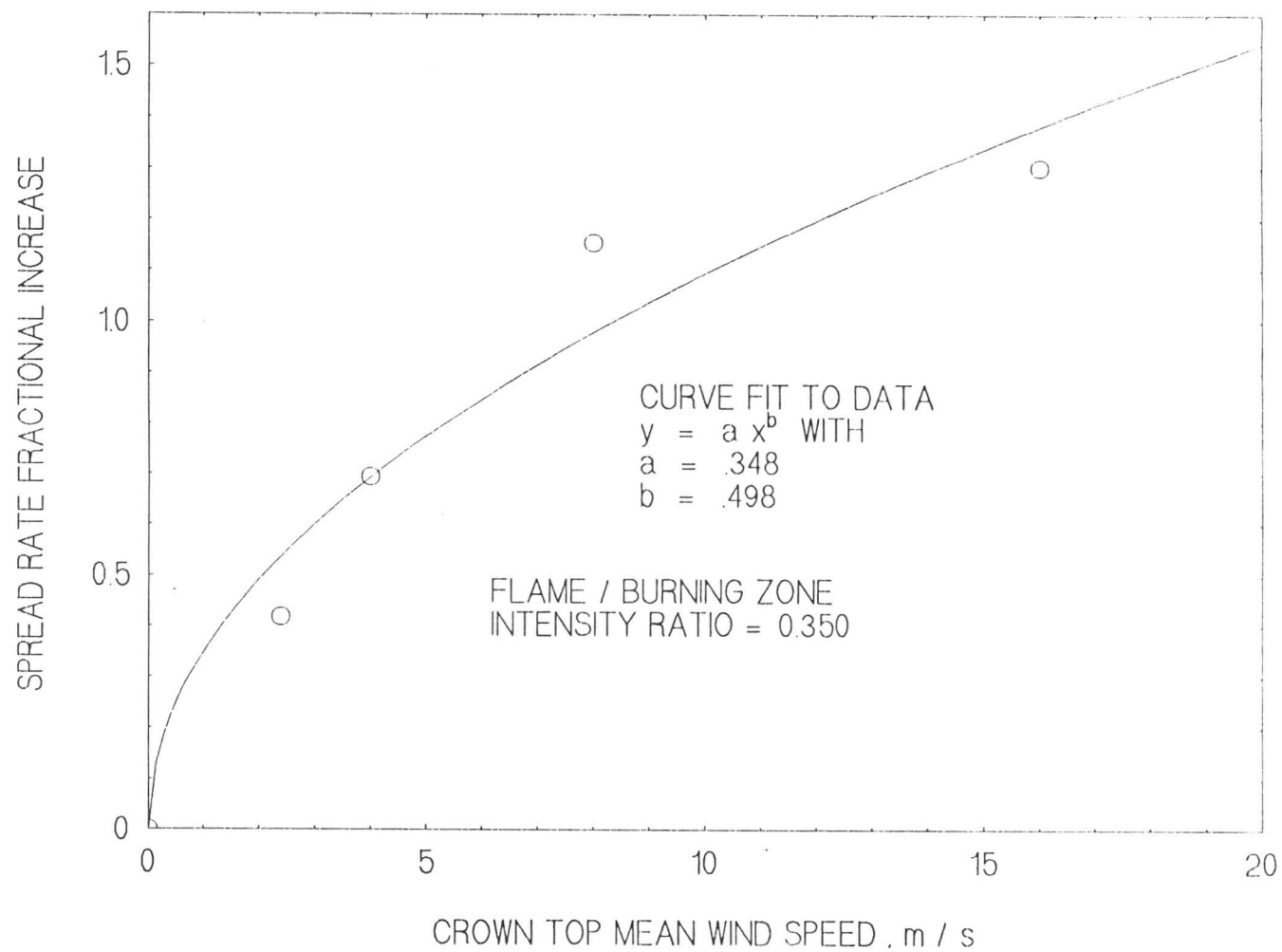
SPREAD RATE INCREASE WITH WIND SPEED -- PLOT A



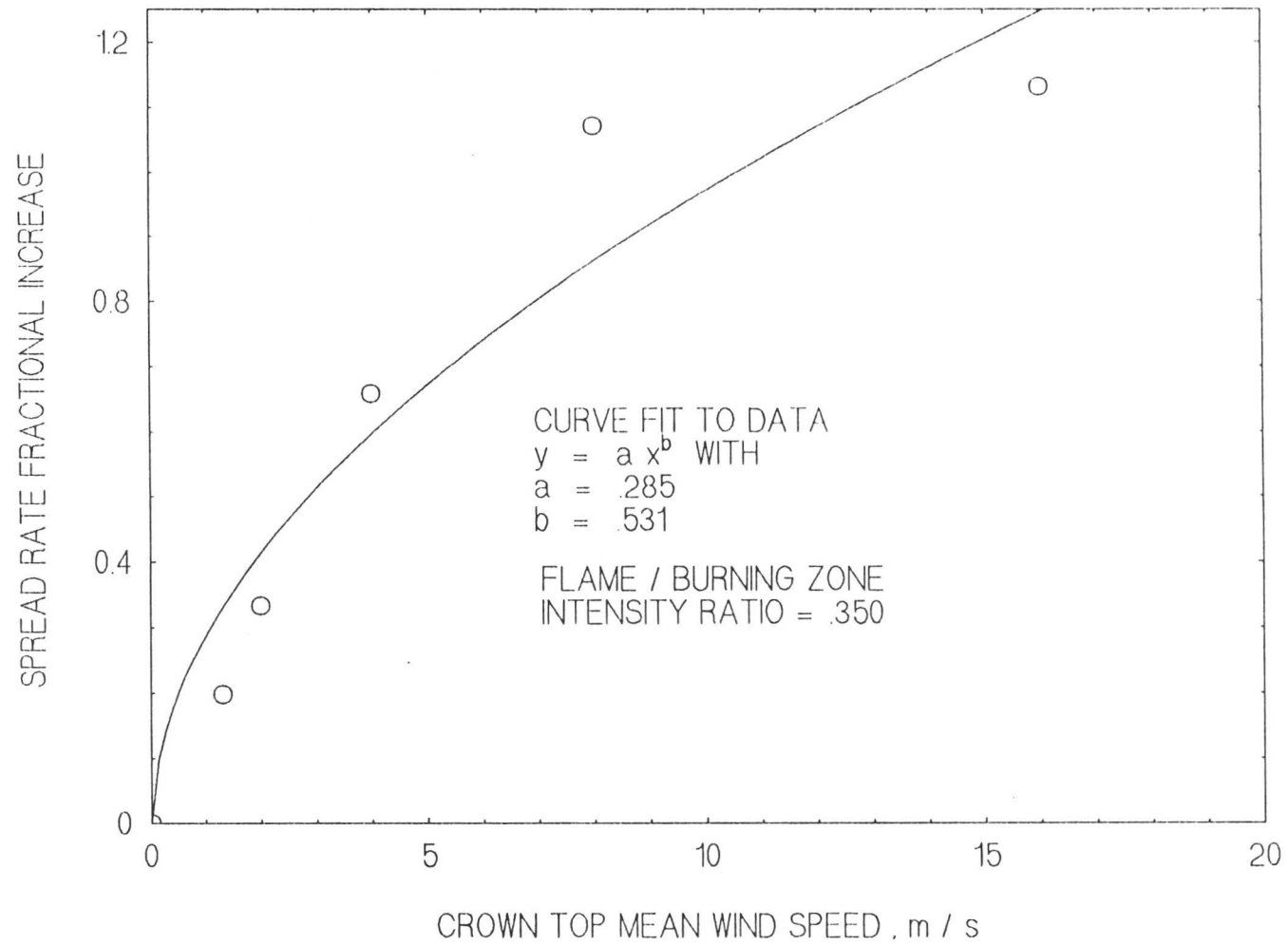
SPREAD RATE INCREASE WITH WIND SPEED -- PLOT A



SPREAD RATE INCREASE WITH WIND SPEED -- PLOT 6



SPREAD RATE INCREASE WITH WIND SPEED -- PLOT 8



SPREAD RATE INCREASE WITH WIND SPEED -- SEVERAL CASES

